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BUYER'S GUIDE

Launch Options for the Future

Special Report

CONGRESS OF THE UNITED STATES OFFICE OF TECHNOLOGY ASSESSMENT
Washington, DC 20510-8025

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Foreword

Adequate, reliable space transportation is the key to this Nation's future in space. Over the next several years, Congress must make critical decisions regarding the direction and funding of U.S. space transportation systems. These decisions include improving existing launch systems, designing and procuring new launch systems, and developing advanced technologies. America's constrained budgetary environment and the lack of a national consensus about the future of the U.S. space program make Congress's role in this process more difficult and important than ever.

In order to decide which paths to take in space transportation, Congress must first decide what it wants to do in space and what it can afford. A space transportation system designed to meet current needs would be woefully inadequate to support a piloted mission to the planet Mars or to deploy ballistic missile defenses. Accordingly, this special report, which is part of a broader assessment of space transportation requested by the House Committee on Science, Space, and Technology, and the Senate Committee on Commerce, Science, and Transportation, takes the form of a "buyer's guide" to space transportation. It describes the range of launch systems that exist now or could be available before 2010 and explores the costs of meeting different demand levels for launching humans and spacecraft to orbit. It also discusses the importance of developing advanced technologies for space transportation.

In undertaking this special report, OTA sought the contributions of a wide spectrum of knowledgeable and interested individuals and organizations. Some provided information, others reviewed drafts of the report. OTA gratefully acknowledges their contributions of time and intellectual effort. As with all OTA reports, the content of this special report is the sole responsibility of the Office of Technology Assessment and does not necessarily represent the views of our advisors or reviewers.

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OTA appreciates the valuable assistance and thoughtful critiques provided by the advisory panel members. The views expressed in this OTA report, however, are the sole responsibility of the Office of Technology Assessment. Participation on the advisory panel does not imply endorsement of the report.

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Congressional Alternatives

Congress could choose to support the development of many different types of space transportation vehicles. To determine which of these alternatives is most appropriate and most cost-effective, Congress must first make some broad decisions about the future of the United States in space. A commitment to key space program goals will entail a similar commitment to one or more launch vehicle systems. Although highly accurate cost estimates do not exist, the analysis in this study suggests that some launch systems are more economical than others to accomplish specific missions.

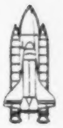
If Congress wishes to:	*Then it should:*
Limit the future growth of NASA and DoD space programs:	*Maintain existing launch systems and limit expenditures on future development options.* **Current capabilities are adequate to supply both NASA and DoD if the present level of U.S. space activities is maintained or reduced.**
Deploy the Space Station by the mid-90s while maintaining an aggressive NASA science program:	*Continue funding improvements to the Space Shuttle (e.g., ASRM and/or LRB)* and/or *begin developing Shuttle-C*: **The current Space Shuttle can launch the Space Station, but will do so more effectively with improvements or the assistance of a Shuttle-C. Although Shuttle-C may not be as economical as other new cargo vehicles at high launch rates, it is competitive if only a few heavy-lift missions are required each year.**
Send humans to Mars or establish a base on the moon:	*Commit to the development of a new unpiloted cargo vehicle (Shuttle-C or Transition launch vehicle or ALS) and continue research and funding for Shuttle II and the National Aerospace Plane.* **A commitment to piloted spaceflight will require a Shuttle replacement shortly after the turn of the century. Large planetary missions will also need a new, more economical, cargo vehicle.**
Continue trend of launching heavier communications, navigation, and reconnaissance satellites and/or pursue an aggressive SDI test program to prepare for eventual deployment:	*Commit to the development of a new unpiloted cargo vehicle (Transition launch vehicle) by the mid-to-late 1990s.* **In theory, current launch systems could be expanded to meet future needs; however, new systems are likely to be more reliable and more cost-effective.**
Deploy SDI and/or dramatically increase the number and kind of other military space activities:	*Commit to the development of a new unpiloted cargo vehicle (Transition Vehicle or Advanced Launch System).* **Current launch systems are neither sufficiently economical to support SDI deployment nor reliable enough to support a dramatically increased military space program.**

Meeting the space transportation needs of specific programs is only part of the reason for making changes to the current launch systems. Congress may wish to fund the development of critical new capabilities or improvements to the "quality" of space transportation, or Congress may wish to ensure that funding serves broader national objectives.

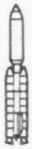
If Congress wishes to:	*Then it should:*
Maintain U.S. leadership in launch system technology:	*Increase funding for space transportation basic research, technology development, and applications.* **Maintaining leadership will require an integrated NASA/DoD technology development program across a range of technologies. Focused technology efforts (ALS, Shuttle II, NASP) must be balanced with basic research.**
Improve resilience (ability to recover quickly from failure) of U.S. launch systems:	*Fund the development of a new high capacity, high reliability launch vehicle (Transition launch vehicle or ALS) or expand current ground facilities or reduce downtime after failures or improve the reliability of current launch vehicles.* **At high launch rates, developing a new vehicle is probably most economical.**
Increase launch vehicle reliability and safety:	*Aggressively fund technologies to provide: 1) improved subsystem reliability; 2) "engine-out" capability for new launch vehicles; 3) on-pad abort and in-flight engine shutdown for escape from piloted vehicles; and 4) redundancy and fault tolerance for critical systems.*
Reduce environmental impact of high launch rates:	*Limit the use of highly toxic liquid fuels and replace Shuttle and Titan solid rocket boosters with new liquid rocket boosters or clean-burning solid boosters.* **The United States will be relying on Shuttle and Titan vehicles through the turn of the century. As launch rates increase, the environmental impact of the Shuttle solid rocket motors and the solid and liquid Titan motors will become more important.**

Launch Systems Discussed in this Report

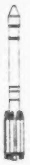
Existing Systems



Space Shuttle—a piloted, partially reusable launch vehicle capable of lifting about 48,000 pounds to low-Earth orbit (LEO). The Shuttle fleet now consists of three orbiters; a fourth is on order. The Shuttle had completed 24 flights successfully prior to the loss of the orbiter Challenger in January 1986.

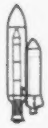


Titan IV—an expendable launch vehicle (ELV) manufactured by Martin Marietta Corporation, which can lift 39,000 pounds of payload to LEO. This vehicle will be launched for the first time later this year, and will be the Nation's highest capacity existing ELV.

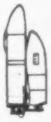


Medium Launch Vehicle—either a Delta II manufactured by McDonnell Douglas, with a lift capability of 7,600 pounds to LEO; or an Atlas Centaur II manufactured by General Dynamics with a lift capacity of about 13,500 pounds to LEO.

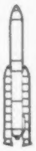
Proposed Systems



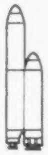
Shuttle-C—an unpiloted cargo vehicle, derived from the Shuttle, with a heavy lift capacity of 100,000 to 150,000 pounds to LEO. It would use the existing expendable External Tank and reusable Solid Rocket Boosters of the current Shuttle, but would replace the orbiter with an expendable cargo carrier.



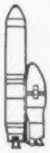
Shuttle II—a fully reusable piloted launch vehicle derived from the current Shuttle. Although Shuttle II is not a firm concept, OTA assumes that it could carry payloads comparable to those carried by the Shuttle but that it would be less costly to operate.



Titan V—a heavy lift ELV derived from the Titan IV. Its payload capacity could range from 60,000 to 150,000 pounds to LEO.



Transition Vehicle—a partially reusable unpiloted launch vehicle with recoverable engines designed to be built with existing technology.



Advanced Launch System (ALS)—a totally new launch system under study by the Air Force and NASA that would be designed to launch large cargo payloads economically at high launch rates. OTA assumes a partially reusable vehicle featuring a flyback booster, a core stage with expendable tanks and payload fairing, and a recoverable payload/avionics module.

Chapter 1

Introduction and Principal Findings

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Chapter 1

Introduction and Principal Findings

INTRODUCTION

Congress must soon make critical decisions about the future of U.S. space transportation. Although these decisions will have a profound effect on the Nation's ability to meet long-term space program goals, they must be made in a highly uncertain environment. A decision to deploy SDI, or to send humans to Mars, would call for space transportation systems of greatly increased capability, and configurations quite different from today's fleet. Alternatively, a decision to maintain the current level of space program activity might be accomplished with existing space transportation systems.

As a result of this uncertainty, projections of future yearly demand normalized to low-Earth orbit (LEO) range from 600,000 pounds to more than 4 million pounds.[1] Such uncertainty makes rational choice among alternative paths extremely difficult. Nevertheless, failing to choose now may leave the United States incapable of meeting future needs.

This special report examines both economic and noneconomic criteria for evaluating these launch systems and presents a "Buyer's Guide" to help the reader choose the launch systems most consistent with his or her own view of the future of the U.S. space program.

In this special report, OTA has analyzed three different mission models (levels of demand) and three different space transportation investment strategies for meeting each level of demand. The mission models describe a range of possible demand levels from 1989 to 2010 (see table 1-1 and figures 1-1 and 1-2).[2] Each model assumes that the United States will maintain a mix of piloted, and medium- and heavy-lift expendable vehicles:

- Low Growth – 3 percent average annual growth in launch rate (41 launches per year by 2010).
- Growth – 5 percent average annual growth in launch rate (55 launches per year by 2010).
- Expanded – 7 percent average annual growth in launch rate (91 launches per year by 2010).[3]

In order to find the most cost-effective way of meeting the lift requirements of each mission model, this special report examines three space transportation investment strategies:

- improving existing launch systems in a series of evolutionary steps;

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[1] Not all payloads have LEO as their final destination. Payloads launched to high orbits require additional upper stages and fuel. OTA has added these upper stages and fuel to the payload masses launched to LEO in order to arrive at a consistent estimate of the total mass launched to space.

[2] OTA assumes that the continuing growth in governmental uses of space, plus the possibility of growth in the commercial uses of space, makes a "No Growth" scenario unlikely. However, chs. 2 and 3 explain that existing or slightly enhanced launch systems could support a limited or no-growth space program.

[3] Although 91 launches per year may seem high relative to recent U.S. experience, it is important to note that in 1966 the United States did launch 73 vehicles. Also, the Soviet Union has averaged 94 launches per year since 1974. (TRW Space Log, TRW Space and Technology Group, Redondo Beach, CA, 1986).

- designing and developing new launch systems for the mid-90s, using existing technology; or
- investing in the development of new technologies for the next century's launch systems.

These strategies, when applied to the various mission models, suggest seven different combinations of launch systems (see box 1-1). With this information in hand, the concerned congressional "buyer" should be able to match his or her space program goals with an appropriate mix of launch vehicles.

Although OTA believes that the cost estimating methodology used in this special report is representative of the state-of-the-art, current methods for estimating launch system costs are partially subjective and uncertain. Because of this uncertainty, small differences in the estimated costs of launch systems are probably not meaningful and should not be the sole basis for national decisions. In addition, cost estimates for future launch systems that would rely on unproven or undeveloped technologies should be regarded with greater skepticism than estimates for existing or modified launch systems.

Box 1-1. – Space Transportation Options Considered by OTA

OTA estimated the life-cycle costs, from 1989 to 2010, of seven different space transportation fleets. To obtain cost estimates, OTA assumed specific configurations for both existing and proposed launch systems. This list is not comprehensive; other system designs are possible.

Enhanced Baseline Option – features an improved Shuttle with Advanced Solid Rocket Motors (ASRMs), improved Titan IVs with new solid rocket motors and fault-tolerant avionics, medium launch vehicles (MLVs – either Deltas or Atlas-Centaurs), and one additional Titan IV pad. This option could not accomodate the flight rates of either Growth or Expanded models.

Interim Option with Titan IV – features the Titan IV and as many new Titan IV launch facilities as are necessary to accomodate the peak launch rate for each mission model. Also includes existing facilities and launch vehicles now operational or in production (the Shuttle and MLVs).

Interim Option with Titan V – features the Titan V. Also includes unimproved Shuttles, MLVs, unimproved Titan IVs, and additional launch facilities.

Interim Option with Shuttle-C – features NASA's proposed Shuttle-C cargo vehicle. Also includes unimproved Shuttles, MLVs, unimproved Titan IVs and additional launch facilities.

Interim Option with Transition Launch Vehicle – features Transition Launch Vehicle. Also includes unimproved Shuttles, MLVs, unimproved Titan IVs, and additional launch facilities.

Future Option with Advanced Launch System (ALS) – features an ALS. Also includes the Shuttle, MLVs, unimproved Titan IVs, and additional launch facilities.

Future Option with Shuttle II – features a Shuttle II. Also includes unimproved Titan IVs, MLVs, and additional launch facilities.

PRINCIPAL FINDINGS

Finding 1: The United States possesses a capable fleet of launch vehicles and the facilities necessary to meet current launch demands and provide for limited near-term growth.

The existing U.S. space transportation fleet consists of the Space Shuttle, a variety of Titan, Delta, and Atlas launch vehicles, and the manufacturing and launch facilities necessary to build and launch these vehicles. Providing that failures are infrequent, these vehicles and facilities are capable of meeting U.S. space transportation requirements at recent historical (1984-85) or even slightly increased levels. The capacity of each system is limited by the rate at which the vehicles can be produced at the factory and flown from the launch pads. With existing vehicles, launch pads, and manufacturing facilities, the United States could launch a maximum of 860,000 pounds per year to low-Earth orbit (LEO).[4] To put such performance in perspective, consider that the United States launched about 600,000 pounds to LEO in 1984 and 1985, while the average for the period 1980-85 was about 400,000 pounds to low-Earth orbit per year. Until the Challenger disaster and the succession of expendable launch vehicle (ELV) failures in 1985 and 1986, the U.S. launch vehicle fleet was meeting military and civil demand reasonably on schedule.

Should the United States choose to use its existing space transportation assets more aggressively, these assets would support limited program growth once the current backlog of payloads is flown off. Current launch systems should be sufficient to support the continuation of existing programs and the increase in launch demand required by the Space Station. However, they could not provide enough lift capacity or the low launch costs sought for SDI deployment, although they could support some SDI experiments.

This is, however, a best-case scenario. Considerable uncertainty exists concerning the Shuttle's lift capabilities and achievable flight rate. In addition, recent Shuttle and ELV failures have shown that existing launch systems lack "resilience," that is, they do not recover rapidly from failure. To increase the resilience of its launcher fleet, the United States may wish to invest in new launch vehicles that it believes can be made more reliable. Resiliency could also be achieved by improving the reliability of existing launch vehicles or reducing the periods of inactivity ("downtime") following launch failures[5] or building backup launch vehicles and pads, as well as payloads.

Finding 2: The incremental improvement of current vehicles and facilities could provide a low-cost means to enhance U.S. launch capabilities.

The United States possesses the technology to improve the capabilities of existing launch vehicles and facilities through evolutionary modifications. For example, incremental improvements to current systems could reduce their operations cost and increase their lift capacity. If improvements in vehicle reliability can be achieved, then current vehicles could be used with greater con-

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[4] This number signifies the estimated upper bound of the system's capacity, not the historical launch capacity. To reach 860,000 pounds per year the United States would have to launch 9 Space Shuttle flights, 6 Titan IVs, 4 Titan IIIs, 5 Titan IIs, 4 Atlas-Centaurs, 12 Delta IIs, and 12 Scouts.

[5] The United States could increase resiliency by adopting a policy of launching immediately after a failure. However, the existence of one-of-a-kind payloads and the high-profile nature of piloted spaceflights make such a change in policy inappropriate.

Table 1-1.—Mission Model Activities

NASA missions	Low Growth	Growth	Expanded
Spacelab	X	X	X
Space Station deployment and operation	X	X	X
Orbital Observatories	X	X	X
Unpiloted lunar and planetary	X	X	X
High-altitude servicing		X	
Station capability growth		X	
Piloted lunar or planetary			X*
DoD missions			
Meteorological	X	X	X
Communications	X	X	X
Defense Support Program	X	X	X
Navigation	X	X	X
Support Missions	X	X	X
Space Test Program	X	X	X
Improved Surveillance		X	
Demonstrations		X	
Advanced Capabilities		X	
SDI System Deployment			X*

* OTA's Expanded mission model could support either deployment of a Phase 1 Strategic Defense System or a major NASA piloted lunar or planetary mission, but not both.

Box 1-2.—Effect of Heavy-Lift Launch Vehicles on Mission Models

Introducing a new heavy-lift launch vehicle would have a profound effect on the demand for other vehicles in the U.S. launch fleet. In its attempt to account for this influence, OTA has made the following assumptions:

- A new heavy-lift vehicle will be able to carry all the large cargo in the mission models with 20 percent fewer flights; that is, two of five payloads could piggy-back on one heavy cargo vehicle;
- 20 percent of Shuttle or Shuttle II payloads could fly on the heavy-lift launch vehicle on a one-for-one basis; that is, 20 percent fewer Shuttle or Shuttle II and 20 percent more heavy-lift vehicle launches would be required;
- Because they could fly on a space-available basis, 30 percent of MLV-class payloads could piggyback on heavy-lift vehicles without increasing the number of heavy-lift vehicle launches required.

Figure 1-1 shows the launch rates of the three mission models for options **without** heavy-lift vehicles, and Figure 1-2 shows the lower launch rates for options **with** a heavy-lift vehicle that would begin operations in 1995. Comparing these two sets of launch rates indicates that the addition of a heavy-lift vehicle reduces the number of flights required for all mission models.

With or without a heavy-lift launch vehicle, this report assumes that the number of piloted and light cargo vehicle flights required for the Growth and Expanded mission models will be no greater than that required for the Low Growth mission model. Holding the number of piloted and light cargo flights constant assumes that ambitious piloted (e.g., mission to Mars or the Moon) or military missions (e.g., SDI deployment) will increase demand for large cargo transport much faster than the demand for human or small cargo transportation. Furthermore, it assumes that a large cargo vehicle can carry some payloads that would have otherwise been launched on either small or piloted vehicles. These assumptions notwithstanding, the more vigorously the United States pursues programs involving humans in space, the sooner it will have to replace or augment the existing Space Shuttle.

Figure 1-1.—Launch Rates Without a Heavy-Lift Launch Vehicle

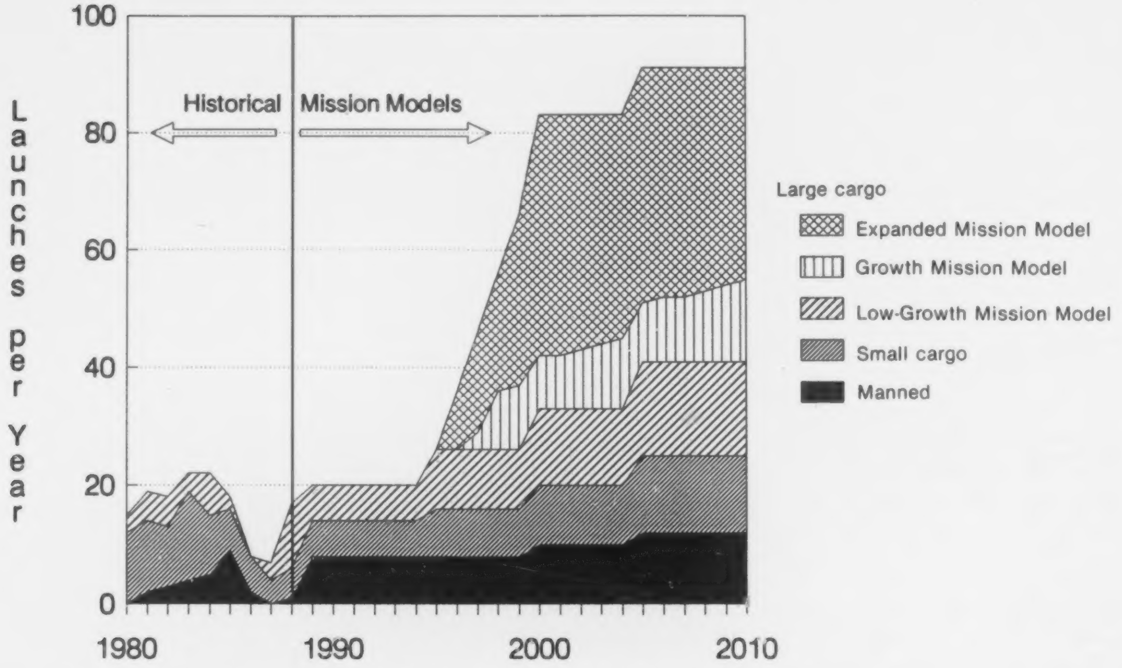


Figure 1-2.—Launch Rates With a Heavy-Lift Launch Vehicle

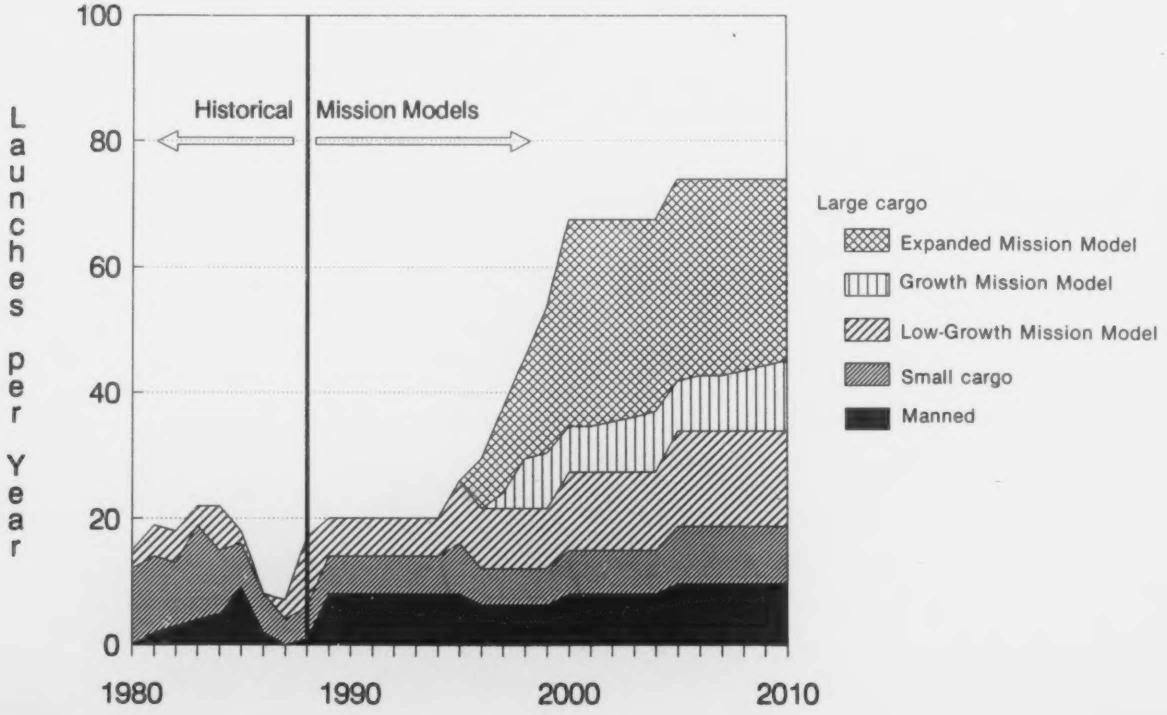
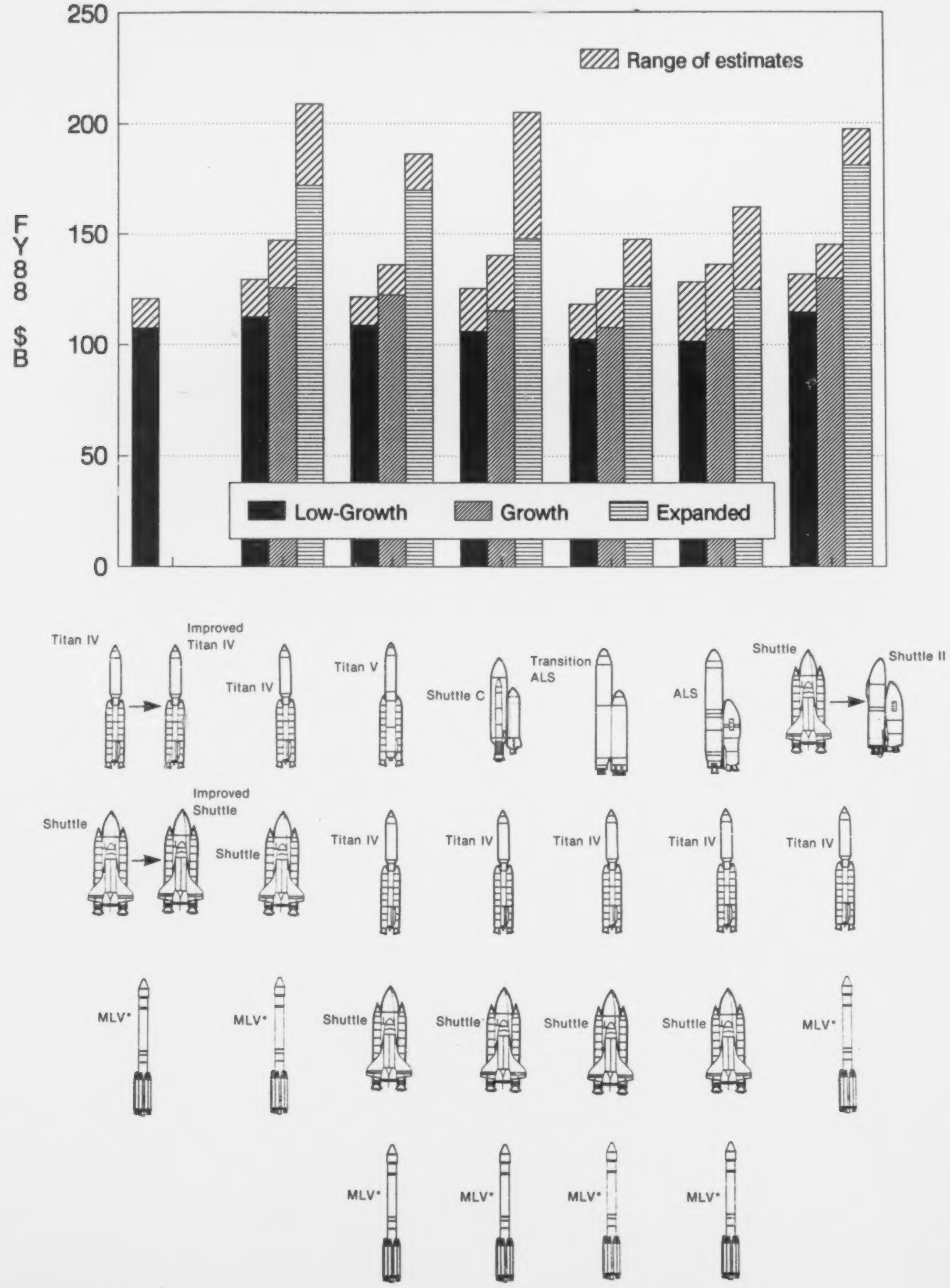


Figure 1-3.—Ranges of Estimates of Life-Cycle Costs (1988 dollars, discounted at 5 percent)



*Medium Launch Vehicle

SOURCE: Office of Technology Assessment, 1988.

fidence at higher flight rates. By improving existing vehicles and ground facilities and buying more launch vehicles, the United States could easily increase its launch capabilities to 1.4 million pounds to LEO per year.[6] Such a launch capability would support a space program with slow growth for many years.

One proposed Shuttle improvement under study is the development of Advanced Solid Rocket Motors (ASRMs). ASRMs are projected to increase the Shuttle's lift capacity by 12,000 pounds, improve Shuttle reliability, and allow the Space Station to be deployed in fewer flights and with less assembly in space. Planned improvements to the Titan IV solid rocket motors would increase the Titan IV's payload capability to LEO from 40,000 to 48,000 pounds.

Other possible enhancements for both the Shuttle and ELV launch systems include:

- improved liquid rocket engine components;
- new ground processing technologies;
- advanced avionics and flight software;
- new high-strength, light-weight materials; and
- new launch pads and flight control facilities.

Although the cost of development and the technical risks of such evolutionary improvements would be low compared to developing new vehicles, only small operating cost reductions could be expected.[7] Because the cost of launch failures is so high, improving the reliability of current vehicles would also be a desirable goal and would result in cost savings. Failing to increase the reliability of current vehicles would make it difficult to fly them at higher rates, since at higher rates failures would be more frequent. Unless other measures were taken, more frequent failures would reduce the periods of activity between "downtimes" and could result in substantial flight backlogs.[8]

The improved versions of existing vehicles contained in OTA's Enhanced Baseline could be used to launch the payloads in the Low-Growth mission model, but could not launch the payloads in either of the more aggressive mission models. Figure 1-3 indicates that the cost of using the Enhanced Baseline to meet the Low-Growth mission model might be between $110 billion and $120 billion.[9] This would be comparable to accomplishing the same task with a fleet of vehicles that included the Transition launch vehicle ($100 billion to $120 billion). Given the uncertainties in cost estimation, the life-cycle costs of these two fleets of launch vehicles are practically indistinguishable at the Low-Growth mission model.

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[6] To reach 1.4 million pounds, the United States would have to make 13 Space Shuttle flights with Advanced Solid Rocket Motors, and launch 10 Titan IVs with new solid rocket motors, 4 Titan IIIs, 5 Titan IIs, 4 Atlas-Centaurs, 12 Delta IIs, and 12 Scouts.

[7] U.S. Congress, Office of Technology Assessment, Reducing Launch Operations Costs: New Technologies and Practices, OTA-TM-ISC-28 (Washington, DC: U.S. Government Printing Office, in press).

[8] The resiliency problem can be addressed in other ways. See discussion above.

[9] Unless otherwise specified, life-cycle costs are given in 1988 dollars, discounted at 5 percent.

Finding 3: By the mid-1990s, the United States could build a variety of new, more capable launch vehicles, or greatly enhance its ability to launch current vehicles by expanding existing manufacturing and launch facilities.

The United States could develop at least four different types of interim launch systems to add to its current fleet of vehicles:[10]

- NASA has suggested that the Nation develop an unpiloted version of the Space Shuttle, "Shuttle-C," for hauling cargo;
- The Air Force proposed in 1987 to develop a state-of-the-art "Transition" launch vehicle from existing technology that would allow routine operations.[11]
- Some aerospace companies have suggested that growth versions of current launch systems could accomplish the tasks that NASA and the Air Force seek to address with their new launch systems.[12]
- The United States could attempt to improve the reliabilities of current vehicles and greatly increase the number of launch pads and production facilities so that existing launch vehicles could be flown at substantially higher launch rates.

Which, if any, of these Interim Options should be chosen depends in large measure on the tasks they would be asked to accomplish. To some extent, these launch systems compete among themselves because all would be asked to function as the primary cargo vehicle in the U.S. launch vehicle fleet. Unlike some of the very advanced vehicle concepts discussed in the next section, the Interim Options do not involve such novel technology that their development programs can be regarded as ends in themselves.

Current programs and projected funding levels do not "require" an interim launch vehicle or greatly expanded launch facilities; desires for increased resiliency could be satisfied in other ways. Should the United States define programs that greatly increase the demand for space transportation, the specific nature of that demand should determine the nature and timing of any interim vehicle development.

NASA and Air Force estimates indicate that NASA's proposed Shuttle-C could provide the Nation with a heavy-lift launch vehicle in a shorter development time (4 years) and at a lower development cost (about $1 billion) than the Air Force Transition vehicle (about $5 billion over 7 years). However, a derivative of an existing ELV might be developed in a still shorter time and at a lower cost than either the NASA or the Air Force systems.

Examining the life-cycle costs of these vehicles could reverse their attractiveness. Shuttle-C and the ELV derivative would be relatively expensive vehicles to operate at high launch rates. For example, figure 1-3 suggests that to fly the Expanded mission model could cost between $150 billion and $200 billion, using a launch fleet that relied on the Shuttle-C as its heavy cargo vehicle, and between $170 billion and $185 billion, using a fleet that relied on a Titan V. Figure 1-3 suggests that the same mission model might be flown for between $125 billion and $150 billion with a fleet that relied on a new Transition launch vehicle.

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[10] One idea not discussed here is the so-called "Big Dumb Booster," a concept that originated in the 1960s. The concept suggests that a combination of simple technologies, such as pressure-fed engines and welded steel tanks, could substantially reduce launch costs. No thorough analysis has yet been carried out on the life-cycle costs of using such a booster. OTA will publish a background paper on this subject in the Fall of 1988.

[11] In 1987, Congress specifically prohibited the Air Force from pursuing this concept, directing instead that the Air Force only investigate concepts that could offer a tenfold reduction in operating costs.

[12] Martin Marietta, for example, has studied the growth potential of the Titan IV and concluded that by increasing the core diameter and adding additional liquid rocket engines and solid rocket motors, Titans could be produced with lift capacities ranging from 60,000 to 150,000 pounds to LEO. Because the Titan is the largest U.S. expendable launch vehicle, it is used in this special report as one example of how current vehicles could be grown into heavy-lift cargo vehicles. Other existing vehicles may also have this potential.

Shuttle-C and the ELV derivatives would primarily use current flight hardware, so the development risk would be lower than for a new vehicle. This technological commonality is advantageous because the new vehicles might share the demonstrated reliability of the existing flight hardware. On the other hand, failures of current vehicles, when they did occur, could cause derivative vehicles to be grounded if components they have in common caused the problem.

Shuttle-C appears most attractive for NASA-unique (i.e., Space Station or planetary) missions requiring infrequent heavy-lift capabilities.[13] The Transition launch vehicle appears most attractive for routine operations at increased demand levels, such as the Air Force will probably engage in over the next decade. ELV derivatives look most attractive for infrequent demand for launching heavy payloads and might serve both Air Force and NASA needs.

The final Interim Option (Titan IV Option) assumes that the United States would continue to use existing launch vehicles, but would add as many new Titan IV launch and manufacturing facilities as are needed to handle the peak launch rate for each of the mission models. Greatly expanding launch and manufacturing facilities, like the other three Interim Options, would require years to accomplish and investments of billions of dollars. This option might not be viable unless vehicles were made more reliable or the downtime between failures were reduced.

Constructing additional launch facilities would provide insurance against launch vehicle failures that damage or destroy launch pads, like the April 1986 Titan explosion that damaged Vandenberg Space Launch Complex 4. On the other hand, suitable sites in the continental United States for processing and launching large space vehicles are very scarce; a total of only four or five sites remain at Cape Canaveral and Vandenberg Air Force Base. Most of the existing launch pads were originally built in the 1950s and 1960s when environmental restrictions were much less severe. Satisfying the current restrictions on new construction in these environmentally sensitive areas would be a complex, expensive, and time-consuming task.

OTA calculations indicate that for the Low-Growth mission model, the Titan IV Option is reasonably competitive with all other launch vehicle options. This option is much less attractive for the Growth or the Expanded mission models (see figure 1-3).

Finding 4: Emerging technologies offer the promise of new launch systems that could reduce cost while increasing performance and reliability. Such systems would entail high economic and technological risk and would require a sustained technology development program.

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[13] For example, Shuttle-C could reduce from 19 to 12 the number of flights needed to launch the Space Station, reduce the assembly time from three years to 19 months, and reduce the amount of risky on-orbit outfitting of laboratory and habitation modules. In addition, at low flight rates, Shuttle-C might provide a cost-effective alternative for near-term launch capability.

The United States is currently examining three advanced space transportation options. Two of these options – Shuttle II, a follow-on to the Shuttle, and the National Aerospace Plane (NASP),[14] a hypersonic spaceplane – would be piloted. The third concept, the Advanced Launch System (ALS), would be an unpiloted heavy-lift cargo vehicle. All of these programs would use new operational concepts,[15] advanced materials, and advanced manufacturing technologies to increase capability and reduce costs.

The Air Force envisions the ALS as a reliable, heavy-lift launch vehicle able to achieve high launch rates. The ALS is conceptually more mature and technically less challenging than either Shuttle II or NASP and is the focus of a joint NASA/Air Force technology development program.[16] In defining the ALS program, the Air Force asked contractors to start with a "clean sheet of paper" and to emphasize cost efficiency rather than performance as the primary goal. If the ALS program were successful in significantly decreasing the costs of launching payloads, then, as shown in figure 1-3, it might cost between $125 billion and $160 billion to launch the Expanded mission model. OTA's calculations suggest that the Transition launch vehicle would have a comparable ($125 billion to $145 billion), or perhaps lower, life-cycle cost.[17]

The other Future Options, the Shuttle II and the National Aerospace Plane (NASP), may achieve a low cost per flight but not necessarily a low cost per pound to orbit. These two piloted vehicles would appear to have overlapping missions, including personnel transport, servicing and repair trips, and transport of high-value commercial products. One or both of these vehicles may eventually be needed as a replacement for the Space Shuttle; however, in the time period considered by this report, neither appears appropriate as the principal U.S. cargo vehicle.[18]

Of the two, NASP requires greater advances in technology and thus is more risky, but could also have a larger payoff. The high degree of technical and cost uncertainty associated with NASP make it impossible to provide useful cost estimates for its development and use.

In addition to these highly visible programs, several unconventional launch technologies such as laser propulsion, ram cannons, coil guns, and anti-matter rockets are in various stages of study. Because some of these concepts would subject payloads to extremely high accelerations, they could be used only for transporting certain types of cargo. These concepts push launch costs to the minimum but may have high development costs. Still, with continued research one of them may someday provide an inexpensive means for transporting supplies to space.

Meeting the space transportation needs of future programs is only part of the rationale for supporting advanced launch technology development. Other reasons include expanding the U.S. technology base and promoting space leadership and industrial competitiveness.

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[14] NASP is a research program designed to explore the technical feasibility of hypersonic flight. The specific applications of NASP technology have yet to be determined.

[15] For a detailed discussion of new operational concepts, see: U.S. Congress, Office of Technology Assessment, Reducing Launch Operations Costs: New Technologies and Practices, OTA-TM-ISC-28 (Washington DC: U.S. Government Printing Office, in press).

[16] The ALS Phase I conceptual development activities are to conclude in August 1988. Through these studies NASA and the Air Force seek to document the major design trade-offs and to refine ALS cost, performance, and reliability models. Phase II (design/demonstration) is scheduled to begin in August 1988.

[17] This is the result, in part, of the fact that certain versions of ALS are not assumed to become operational until the year 2000, so their greater development costs cannot be recovered by savings in operations costs before 2010, the last year of the OTA mission model.

[18] Sometime in the 2000s, the current Space Shuttle will begin to exceed its useful lifetime or will become obsolete. At this point, if the United States wishes to continue its human presence in space, a replacement for the current Shuttle will be necessary whether or not it is competitive at launching cargo with then existing or planned cargo vehicles.

Finding 5: An aggressive technology development program could allow the United States to remain preeminent in selected space technology areas. Such a program must balance technology efforts focused on specific launch systems with basic research and technology development.

A variety of experts have expressed concern over the poor state of U.S. space technology development, especially in light of foreign activities, which have increased dramatically over the last decade. Research on basic technologies for launch systems has been particularly neglected. For example, the United States has not developed a new rocket engine in over 15 years and the space program has followed rather than led other industrial sectors in the development and use of new light-weight, high-strength materials and automation and robotics.

An aggressive technology development program would be beneficial to any of the options discussed in this special report. Even if Congress decides to defer development of a new launch system for a few years, investment now in new launch-related technologies would prepare the United States to proceed more quickly in the future. The Air Force and NASA budget submissions for fiscal year 1989 contain funds to begin such technology developments, but at a level of effort that appears low relative to that recommended by numerous recent studies.

Finding 6: The most appropriate economic measure of merit for comparing different launch system options is discounted life-cycle cost. Noneconomic criteria such as "space leadership" or international competitiveness must also be weighed in choosing among options.

Minimizing a launch system's upfront costs (technology development, vehicle design, and facilities) is often done at the expense of driving up its recurring costs (fuel, expendable components, personnel). The least cost to the taxpayers is incurred by minimizing total life-cycle costs – the sum of all upfront and recurring costs, including costs of failure – discounted to reflect the value of money over time. This special report assumes a 5 percent real discount rate, which is generally accepted for government investments. A higher discount rate would penalize options that require greater upfront investments.

Estimated life-cycle cost cannot be the sole criterion for decisions on launch system development. The United States may prefer to sacrifice some life-cycle economy for other benefits, such as near-term affordability or noneconomic benefits such as "leadership" or national security. Some advanced programs require large investments and promise no immediate pay-back but would contribute to the status of the United States as a technology innovator. Other investments, although uneconomical, might be needed to counter the military activities of our adversaries.

Finding 7: Demand for launch services is the most important determinant of the value of investing in new launch systems.

If future missions are as infrequent and diverse as they have been in the 1980s, no option reviewed by OTA appears likely to reduce average launch costs significantly, although several could provide improved reliability, capability, and resiliency. However, if over the next 20 years demand for launch services continues to increase, it would become economical to develop and procure new launch vehicles that could be processed and launched efficiently at high launch rates. Small payloads that could be co-manifested with others would benefit even more from such new vehicles. However, until the country decides whether to deploy SDI, revisit the Moon, explore Mars, embark on some other major space project, or limit space activities to those requiring only modest budget increases, accurate projections cannot be made of either the number or type of space transportation vehicles and facilities that will be needed. Such projections are essential if new facilities or vehicles are to be designed for maximum economy.

Finding 8: At Low-Growth launch rates it is uncertain whether it is more desirable to invest in new vehicle technology or to expand production and launch facilities and incrementally improve current vehicles.

At the launch rates assumed in the Low Growth mission model, none of the options considered by OTA offers a discounted life-cycle cost that is substantially different than that of current vehicles. Because the differences in life-cycle cost are small, choices among the options must be based on other economic criteria, such as magnitude of near-term investment or peak annual funding, or on noneconomic criteria such as lift capability and reliability.

New launch vehicles could lift heavier payloads or improve reliability and resiliency, but would require more investment than current vehicles or improved versions of current vehicles. Upgrading existing vehicles would have low development costs but would save less on operations costs. In addition, launching current vehicles at high rates would require improvements in reliability, backup launch vehicles and facilities, or reductions in "downtime" following failures. If such changes could not be achieved economically with current vehicles, then the most advisable course would be to pursue a new cargo vehicle.

The inability of current vehicles to meet specific near-term needs would also provide a reason for developing new launch capabilities. For example, should the United States determine that it requires a Shuttle-C for Space Station or that it has a payload too large for the Titan IV, then a new vehicle might be appropriate. In such circumstances, the specific nature of the need should be allowed to dictate the nature of the new vehicle.

Finding 9: At Growth launch rates it appears that the development of a Transition launch vehicle might yield savings.

At Growth mission model levels, OTA estimates that the Transition launch vehicle would cost between $110 billion and $125 billion (see figure 1-3). Judged according to these cost estimates, the life-cycle cost of the Transition launch vehicle could be as much as 10 percent less costly than either the Titan V or the ALS. In addition, the Transition vehicle might have greater reliability, and less environmental impact at high launch rates than a Titan V and would entail less development cost than the ALS.

Finding 10: At Expanded launch rates the Transition launch vehicle or the Advanced Launch System should both yield savings.

If launch rates more than quadruple by 2005, with heavy cargo launch rates increasing more than tenfold, an Advanced Launch System or less advanced Transition launch vehicle should have lower life-cycle costs than the other options considered by OTA.

Finding 11: Current methods for estimating launch system costs are subjective and unreliable. Improving the science of cost estimation should be part of any launch vehicle or technology development program.

Even if future demand were known, estimated costs of launch systems would still be highly uncertain because the United States' space transportation operations experience is limited compared to the mature commercial aviation industry and a highly detailed database is unavailable. Although the Space Transportation Architecture Study[19] improved cost estimating models and these models continue to be improved in the NASA/Air Force ALS studies, much work is still needed to find and aggregate historical cost data, record and analyze more system details, make uncertainties more explicit, and develop the means to estimate the effects of new technologies on manufacturing costs and launch system operations. Congress may wish to direct the Air Force and NASA to increase their effort to develop new, more credible cost estimation models.

Finding 12: Large development projects for new space transportation systems are not likely to achieve their cost or technical objectives without continuity in commitment and funding.

The ultimate cost of any large system depends, in some degree, on how it was purchased. The nature of the annual budgeting and appropriations process often causes yearly fluctuations in the continuity of development funds, or delays in purchasing systems and facilities. These effects can produce significant increases in the cost of large systems. When examining the credibility of any launch system cost estimate, Congress must take into account the effect of its own actions on program costs.

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[19] U.S. Department of Defense and National Aeronautics and Space Administration, National Space Transportation and Support Study 1995-2010, Summary Report of the Joint Steering Group, May 1986, pp. 15-19.

Chapter 2

Current Launch Systems

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Chapter 2

Current Launch Systems

CAPABILITIES OF CURRENT LAUNCH SYSTEMS

In the early 1980s, the United States began to implement a policy that would have eventually resulted in the United States relying solely on the Space Shuttle for access to space. The Challenger disaster ensured that ELVs will again play an important role in our national launch strategy. In various stages of production are the replacement Shuttle orbiter[1] and 57 ELVs ordered by the Air Force: 23 Titan IVs, 20 Delta IIs, and 14 Titan IIs. The Air Force has reassessed its launch needs through 1995 and anticipates (as of June 1988) a need for an additional 45 ELVs – 20 Titan IVs, 11 Delta IIs, 11 MLV IIs, and 3 Titan IIs. NASA plans 35 ELV and 53 Shuttle flights by the end of 1993.[2] This chapter provides a "snapshot" of current launch systems and their capabilities so that the launch system options discussed in chapters 3-5 can be compared to a baseline.

These planned flight rates represent a considerable launch capability if they can actually be achieved. Launch capacity depends not only on the lift capabilities of existing United States launch vehicles, but on their maximum production rates using present manufacturing facilities, and their maximum sustainable (steady state) flight rates at existing launch facilities.[3] As shown in table 2-1, existing manufacturing and launch facilities have sufficient capacity to meet planned flight rates for NASA and DoD ELVs, with the possible exception of the Titan IV. The Air Force has requested funds to augment Titan IV production and launch capability.

The amount of lift capacity provided by the Space Shuttle depends on how many orbiters are in the fleet and the maximum Shuttle flight rate. The calculation in table 2-1 evaluates the capabilities of a three-orbiter Shuttle fleet with a maximum annual flight rate of nine.[4]

The amount of lift capacity provided by ELVs is limited by the lower of their maximum annual production rates and their maximum launch rates. Currently, these rates limit the United States to about 12 Scout, 12 Delta II, 4 Atlas/Centaur, 5 Titan II, 4 Titan III, and 6 Titan IV launches per year. This includes NASA, DoD, and commercial launches.

Table 2-1 shows that the maximum space launch capacity available to the U.S. using existing vehicles, facilities, and factories is roughly 860,000 pounds per year to low-Earth orbit (LEO). To put this number in perspective, the United States launched about 600,000 pounds per year in the two years prior to the Challenger disaster (1984 and 1985).[5]

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[1] The first flight of OV105, the replacement fourth orbiter, is scheduled for January 1992.

[2] Thirteen of those Shuttle flights are reserved for DoD payloads. U.S. National Aeronautics and Space Administration, "Payload Flight Assignments" (Washington, DC: Office of Space Flight, March 1988).

[3] Launch vehicles typically come in several versions with different capabilities depending on the upper stages used. Although the launch vehicles in this figure are representative examples, they do not provide a comprehensive catalog. The performance figures cited refer to a specific version. All values are normalized to a common reference orbit; performance to other orbits will vary depending on the orbit selected.

[4] Because of bottlenecks in the Shuttle processing flow, the National Research Council estimated the maximum sustainable Shuttle flight rate with a three orbiter fleet to be 8-10, and 11-13 with a four orbiter fleet. See National Research Council, Committee on NASA Scientific and Technological Program Reviews, Post-Challenger Assessment of Space Shuttle Flight Rates and Utilization (Washington DC: National Academy Press, October 1986).

Thus, current unimproved facilities give the United States room for limited expansion of its space launch activity.

Table 2-1.— Maximum Lift Capability of U.S. Launch Vehicles Using Existing Manufacturing and Launch Facilities

launch vehicle	mass delivered[a]	production rate[b]	launch rate[c]	capability[d]
Scout	570	12	18	6,840
Titan II	5,500	5[e]	5	27,500
Delta II (3920)	7,600	12	18	91,200
Atlas/Centaur	13,500	5	4	54,000
Titan III	27,600	10	4	110,400
Titan IV	39,000	6	6	234,000
Space Shuttle	48,000[f]	n.a.[g]	9	432,000

total = 956,000 pounds

x 90 percent manifesting efficiency[h] = 860,000 pounds

[a] pounds delivered to a 100 nm circular orbit at 28.5° inclination unless otherwise noted.

[b] maximum sustainable production rate with current facilities in vehicles per year.

[c] maximum sustainable launch rate with current facilities in vehicles per year

[d] mass delivered times the lessor of the maximum production rate or the maximum launch rate

[e] In July 1988 the first of 14 planned Titan IIs (retired ICBMs converted into space launch vehicles) is scheduled for launch, with 41 other Titan IIs remaining in storage for potential conversion. Launch Vehicles Overview, Martin Marietta Launch Systems Company, Jan. 21, 1988.

[f] This figure is an average of the three existing orbiters' performance to a 150 nm circular orbit (OV102: 45,600 pounds; OV103 and OV104: 49,100 pounds).

[g] Not applicable since the orbiter is reusable. No orbiter production is currently planned beyond the Challenger replacement.

[h] Vehicles often fly carrying less than their full capacity. Manifesting efficiency is the amount of lift capability that is actually used by payloads or upper stages. Volume constraints, scheduling incompatabilities, or security considerations often account for payload bays less than full by weight.

SOURCE: OTA.

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[5] U.S. Congress, Congressional Budget Office, Setting Space Transportation Policy for the 1990s, A Special Study (Washington, DC: Congressional Budget Office, October 1986), p. 13.

LIMITS OF EXISTING LAUNCH SYSTEMS

The previous section examined theoretical launch rates and capabilities of current systems. However, merely examining "numbers of launches" or "pounds to orbit" does not tell the whole story because existing launch systems have some very important limitations:

A lack of "resiliency" - Simply stated, resiliency is the ability of a launch fleet to maintain schedules despite failures. The resiliency of existing launch fleets was called into question by the ELV and Shuttle launch failures in 1986. In order to increase space transportation resiliency, the Nation could develop new, more reliable launch systems. Alternatively, it could make existing vehicles more reliable, reduce the period of inactivity after failures, or increase the ability to "surge" by buying extra vehicles and payloads to launch at high rates following failure. In addition, the United States could design critical payloads to enable them to be flown on more than one launch vehicle, when possible. Box 2-1, "Improving The Resiliency of United States Launch Systems," describes these resiliency options in greater detail.

High launch costs - Current launch costs are between $3,000 and $6,000 per pound delivered to low-Earth orbit. Such costs limit the amount of civilian, military, and commercial space activity that the United States can reasonably afford. For example, payload sizes in some SDI mission models are compatible with today's launch vehicles, but launch costs using current vehicles would be unacceptably high because too many launches would be required. A baseline SDI Kinetic Energy Weapon architecture calling for lifting 40 million pounds into orbit would have a transportation cost alone of $120-240 billion using today's vehicles.[6] Similarly, civilian activities that would necessitate lifting millions of pounds to orbit, such as a human expedition to Mars, would require a reduction in launch costs to be affordable.

On the other hand, the costs of payloads, which can cost between $20,000 and $60,000 a pound, may prove the ultimate limitation on the exploitation of space. As pointed out in a recent report by the Congressional Budget Office,[7] dramatic increases in launch demand would require a concomitant increase in total budget outlays in order to pay for additional payloads.

Shuttle flight rate uncertainties - The Nation has far less experience with Shuttle processing than with ELV processing. Thus, planned Shuttle flight rates may be optimistic, as has been the case in the past. In 1989, as shown in table 2-1, NASA plans nine Shuttle flights,which would tie the record for the most flights ever made in a single year with three orbiters. The added check-out procedures instituted in response to the Challenger disaster could make a return to this launch rate unlikely in the near future.

Limits on payload size - Using the Shuttle, the United States has the ability to launch payloads up to 48,000 pounds into LEO, or about 10,000 pounds into geosynchronous orbit.[8] Both NASA and DoD space programs could benefit from a launch vehicle with a greater lift capacity.

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[6] At a launch cost of $3,000 to $6,000 per pound.

[7] See U.S. Congress, Congressional Budget Office, The NASA Program in the 1990s and Beyond (Washington, DC: Congressional Budget Office, May 1988).

[8] For comparison, when the Soviet Energia becomes operational it will be capable of launching about 220,000 pounds into LEO, about as much as the Apollo program's Saturn V was able to lift.

Using the present Shuttle to launch Space Station laboratory and habitation modules will limit the amount of equipment that can be integrated within the modules on the ground. The rest of the equipment will have to go up separately and be installed on-orbit. This will require a substantial amount of difficult, and potentially hazardous, extravehicular activity (156 man-hours) and on-orbit outfitting.[9] A new vehicle with greater lift capacity would also aid in the launch of large planetary missions. Using current vehilces, missions like the proposed Mars Sample Return, would require spacecraft to be launched in several segments and assembled in orbit.

Similarly, the trend of using increasingly larger communications, navigation, and reconaissance satellites suggests that DoD could effectively employ a vehicle with greater lift capacity than current vehicles.[10]

Box 2-1.—Improving the Resiliency of U.S. Launch Systems

After the Shuttle and ELV launch failures in 1986, the Air Force developed a theory of space transportation "resiliency" to explain the impact that launch system failures have on payloads waiting for launch.[a]

A launch vehicle failure has two principal impacts. First, it can destroy unique, expensive payloads, such as the Hubble Space Telescope or critical national security satellites used to monitor arms control agreements. Second, after a launch failure, the government orders the fleet to "stand down" until the cause of the accident is determined and corrected. A standdown creates a backlog of payloads that slows programs, limits planned missions,[b] and generates unexpected expenses.[c] Reducing the backlog can require flying launch vehicles at a higher rate than normal which, in turn, can increase the probability of failure.

To increase the resilience of its launcher fleet, the United States could pursue one or more of the following alternatives:

- *Develop new, more reliable launch systems*—Some government and industry experts believe that technology available today could be incorporated into designs for new launch vehicles, making them more reliable and faster to prepare and launch than current vehicles. Of course, developing any new space launch vehicle is a challenging task involving significant technical and financial risk.
- *Increase the reliability of current launch systems*—Where possible, some subsystems on existing vehicles could be replaced with new, more reliable subsystems, increasing the systems' overall reliability and resilience. Efforts currently underway include developing fault-tolerant avionics and upgraded solid motors for the Titan IV, and Advanced Solid Rocket Motors for the Shuttle. Still, no launch system, including the Shuttle, can be made 100 percent reliable.[d]
- *Increase current ground facilities and buy more existing launch vehicles and payloads*—When a failure occurs, the United States tends to interrupt launch activities until the malfunction can be identified and corrected. Following this stand down, the launch system must "surge," that is, fly payloads more frequently than planned, to work off the accumulated backlog. Expanding ground facilities and building additional launch pads, launch vehicles, and payloads would improve resiliency by reducing the time it takes to fly off the backlog and return to normal operations.

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[9] National Research Council, Report of the Committee on the Space Station, (Washington, DC: National Academy Press, September 1987), p. 22.

[10] An Aerospace Corporation study projects that by the mid-1990s the Air Force may seek to place payloads weighing 14,000 pounds into geosynchronous orbit. This would require the ability to deliver a minimum of 57,000 pounds to LEO. Aerospace Corporation, "Air Force-Focused Space Transportation Architecture Study," Report No. TOR-0086A(2460-01)-2, August 1987.

A decision to deploy space-based ballistic missile defenses would also require vehicles capable of launching large monolithic payloads to space.

Environmental concerns - Current solid rocket motors produce hydrochloric acid as a combustion byproduct. If the Nation were to continue to use these solid rocket boosters on its launch vehicles, environmental considerations would at some point limit their allowable launch rates.[11] However, as part of the ALS technology program, researchers at the Air Force Astronautics Laboratory are studying solid propellants that not only have clean exhausts, but improved performance and lower cost than the Shuttle propellants.

The highly toxic storable liquid propellants, such as the nitrogen tetroxide and monomethylhydrazine used used to power the core engines of Titan launchers, might

- *Change U.S. policy and cease to stand down after launch failures* – When a U.S. aircraft crashes, rarely is the entire fleet of similar models grounded. The Soviet Union has generally maintained an aircraft-like "launch after failure" philosophy while the U.S. – mainly because of the high cost and unique nature of certain payloads (including piloted flights) – tends to stand down. Not standing down means that no backlog is developed and no surge is necessary. Launch systems are flown at their normal, steady-state flight rate. Most aircraft failures do not result in standdowns because of the experience base and confidence we have in aircraft reliabilities. Until we have similar confidence in launch system reliabilities it may be difficult to change this standdown policy.
- *Design payloads for flight on several launch vehicles, when possible* – If payloads and launch vehicles had compatible, interchangeable interfaces, then operational flexibility would be increased and resiliency might be increased. A critical satellite manifested for a launch vehicle currently standing down could be remanifested for an operational launch vehicle. A limitation of this option is that payloads designed for the heaviest booster in the fleet would have no backup launch vehicle. Moreover, if the backup vehicle is less reliable than the primary vehicle, there would be a greater chance of payload loss.

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[a] Harry Bernstein and A. Dwight Abbott, "Space Transportation Architecture Resiliency," Working Paper, (El Segundo, CA: The Aerospace Corporation, March 1987.) A specific mix of launch systems is considered resilient if it has the ability to recover rapidly from failures, and maintain launch schedules.

[b] Diminishing launch capacity can cause delays and cancellations of lower priority (commercial and research) payloads so that the most urgent payloads (national security and planetary payloads with critical launch windows) can be flown. About 70 Shuttle equivalent flights over ten years were eliminated from the Nation's launch plans as a result of the space transportation crisis. Source: NASA, Office of Space Flight, briefing to OTA, Feb. 8, 1988.

[c] One contractor estimated the cost of the Challenger accident (including the costs of replacing the orbiter, replacing the cargo, investigating the accident, redesigning the flawed parts, and delaying the launch schedule) to be upwards of $13.5 billion.

[d] A recent National Research Council report stated, "... the nation must realize that the Shuttle orbiter fleet is likely to continue to suffer occasional attrition." National Research Council, *Report of the Committee on the Space Station*, (Washington DC: National Academy Press, September 1987), p. 24. Rockets will fail occasionally, sometimes catastrophically.

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[11] OTA has not conducted an independent analysis of the environmental effects of using the current generation of solid rocket motors at high launch rates. It has also not studied the environmental effects of liquid propellants.

cause considerable environmental concern if used at very high launch rates. Other, less toxic liquid propellants, which also produce clean exhaust products, are being studied.

Chapter 3

Enhanced Baseline

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Chapter 3

Enhanced Baseline

The ENHANCED BASELINE option is the U.S. Government's "Best Buy" if ... it desires a space program with current or slightly greater levels of activity. By making incremental improvements to existing launch vehicles, production and launch facilities, the U.S. could increase its launch capacity to about 1.4 million pounds per year to LEO. The investment required would be low compared to building new vehicles; however, the adequacy of the resulting fleet resiliency and dependability is uncertain. This option would not provide the low launch costs (e.g. 10 percent of current costs) sought for SDI deployment or an aggressive civilian space initiative, like a piloted mission to Mars.

IMPROVING THE SHUTTLE

The Shuttle, though a remarkable technological achievement, never achieved its intended payload capacity and recent safety modifications have further degraded its performance by approximately 4,800 pounds. Advanced Solid Rocket Motors (ASRMs) or Liquid Rocket Boosters (LRBs) have the potential to restore some of this performance; studies on both are underway. Other possible options include manufacturing the Shuttle External Tank (ET) out of lighter materials, and improving the Shuttle ground processing flow to increase the Shuttle's launch rate.

Advanced Solid Rocket Motors (ASRMs)

The ASRM program goals are to improve Shuttle safety and performance significantly by:

- designing the field joints to close rather than open when pressurized,
- reducing the number of factory joints and the number of parts,
- designing the ASRMs so that the Space Shuttle Main Engines no longer need to be throttled during the region of maximum dynamic pressure,
- replacing asbestos-bearing materials,
- incorporating process controls and automation to eliminate labor intensive operations and improve motor quality, reproducibility, and safety.[1]

An example of the savings potential offered by improved process control is Hercules' new, automated, solid rocket motor manufacturing facility for the Titan IV solid rocket motors. Compared to an older United Technologies facility where the workforce is around 35, Hercules can cast four times the propellant at a time with one-tenth the personnel.[2]

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[1] RADM Richard Truly, NASA Associate Administrator, Office of Space Flight, testimony before the House Committee on Science, Space, and Technology, Subcommittee on Space Science and Applications, on Advanced Solid Rocket Motors, April 1988.

[2] Air Force Space Division, Los Angeles, CA, Briefing to OTA, Dec. 4, 1987.

ASRMs would add an estimated 12,000 pounds of lift to the Shuttle, allowing it to lift 61,000 pounds to a 150 nm orbit.[3] At the proposed Space Station orbit (220 nm), ASRMs could allow a Shuttle to lift 58,000 pounds instead of 46,000 pounds, significantly aiding Space Station deployment. The first phase of Space Station deployment is presently scheduled to take about three years and 19 Shuttle flights. With ASRMs this could be accomplished with five fewer flights in four fewer months.[4] Furthermore, if even more capability were desired, NASA could decide to develop LRBs or ASRMs capable of lifting 15,000 rather than 12,000 additional pounds.

NASA believes that ASRMs would require about 5 years and $1 to $1.5 billion for design, development, test, and evaluation. A set of ASRMs could cost $40 to $50 million, or slightly more than the cost of present Solid Rocket Boosters.[5]

Liquid Rocket Boosters (LRBs)

In parallel with the ASRM studies, NASA is studying ways to enhance the Shuttle's performance by replacing the SRBs with LRBs. Like ASRMs, LRBs could be designed to provide an additional 12,000 pounds of lift over present SRBs. In September 1987 General Dynamics and Martin Marietta began LRB conceptual design studies. The analyses will consider performance, safety, reliability, costs, environmental impact, and ease of integration with the Shuttle and launch facilities. In the early 1970s NASA compared solid and liquid booster technology for use on the Shuttle. NASA chose solids because it estimated that the liquid booster would cost from $0.5 to 1.0 billion more to develop than a solid rocket motor.[6]

LRBs should have several advantages over SRBs. A flight-ready set of LRBs could be test-fired before they were actually used on a mission. LRBs might also improve the range of launch abort options for the Shuttle, compared with existing SRBs or ASRMs. LRBs can be instrumented and computerized to detect imminent failure and to select the safest available course of action. Unlike solid boosters, that burn their fuel until spent once ignited, LRBs could be shut down or throttled up if necessary to abort a launch safely. Launch operators could also change the thrust profiles of LRBs if mission requirements dictated, while SRB segments follow a specific thrust profile once cast. One-piece LRBs should have shorter processing times than segmented SRBs, which needed about 21 days for stacking before the Challenger accident, and around 70 days for the first post-Challenger flight. LRBs might provide a more benign payload environment than SRBs as a result of their more gradual start and lower acoustic levels. These factors may also extend the orbiters' lifetimes by reducing structural stress induced by lift-off noise and vibration. LRBs would also produce less environmentally contaminating exhaust products than current SRBs and would eliminate operations involving hazardous propellants in the Vehicle Assembly Building. Finally, LRBs could have applications beyond just the Space Shuttle, including Shuttle-C, an Advanced Launch System, or even as a new stand alone booster with a 50,000 to 80,000 pound lift capacity.[7]

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[3] Even though the unaugmented orbiters (OV103, OV104, and the replacement orbiter OV105) would be capable of lifting 54,000 pounds to orbit, landing weight constraints limit their payload capacity to 49,100 pounds. The earlier, heavier orbiter (OV102) is capable of lifting only 45,600 pounds to orbit.

[4] National Research Council, Report of the Committee on the Space Station of the National Research Council (Washington, DC: National Academy Press, September 1987), and Space Transportation for the Space Station, A NASA Report to Congress, (Washington, DC: NASA Office of Space Flight, January 1988), p. 12.

[5] A set of two new SRBs cost $88 million (1987 dollars) refurbished SRBs cost $35 million. (Gerald Smith, NASA, Office of Space Flight, "Solid Rocket Booster Project," presentation to OTA, Jun. 23, 1987.)

[6] U.S. Congress, House Committee on Science, Space, and Technology, Subcommittee on Space Science and Applications, Space Shuttle Recovery Hearings, Apr. 29-30, 1987, vol. I, p. 64.

Lighter Tanks

Another way to increase the Shuttle's capability would be to make the Shuttle's External Tank out of a new alloy, such as aluminum-lithium, instead of aluminum. Aluminum-lithium offers a 20 to 30 percent weight saving compared to the aluminum alloy now used in the External Tank.[8] If the External Tanks were made of aluminum-lithium and the inter-tanks were made of graphite epoxy, the Shuttle would weigh 12,000 pounds less at lift-off.[9] Since the External Tank is carried nearly all the way to orbit, reducing the weight of the External Tank by 12,000 pounds would translate into almost 12,000 pounds of increased payload capability.

Improving Shuttle Ground Operations

Introducing a number of new technologies and management strategies into Shuttle ground operations could make these operations more efficient, faster, and cheaper.[10] For example, introducing computerized management information systems into launch and mission control facilities could sharply reduce the amount of human effort in making, distributing, and handling paper schedules and information. It could also reduce errors and speed up sign-off procedures.

Another strategy thought to have the potential to decrease Shuttle processing time is developing "mission reconfigurable software" to accommodate rapid, high quality mission-to-mission software changes. Software writing and rewriting is presently a constraint on the Shuttle's turn-around time and consequently, its flight rate. Other improvements to Shuttle ground operations include:

- reducing documentation and oversight,
- developing expert computer systems,
- providing adequate spares to reduce cannibalization of parts,
- developing an automated Shuttle tile inspection system, and
- creating better incentives for lowering costs.

IMPROVING EXISTING ELVs

Over the years, manufacturers have incrementally improved their ELVs, increasing both their payload capacity and reliability. This process continues today as the payload capacity of each major U.S. ELV family is now being increased.

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[7] General Dynamics, Space Systems Division, "An Overview of the Liquid Rocket Booster System," April 1988.

[8] Boeing Aerospace Company, "Space Transportation Architecture Study," Final Report, D524-10008-1, Nov. 30, 1987, pp. 106-107.

[9] Boeing presentation to OTA, February 1988.

[10] U.S. Congress, Office of Technology Assessment, Reducing Launch Operations Costs: New Technologies and Practices, TM-ISC-28, (Washington, DC: U.S. Government Printing Office, August 1988), covers this topic in detail. The savings produced by these technologies and management strategies depends on the launch demand.

Delta

Various Delta configurations have successfully launched 170 spacecraft to orbit as of June 1988. Incremental growth of the Delta over the years has increased its lift capacity to LEO from several hundred to 8,000 pounds.[11] McDonnell Douglas is now considering the next steps in the Delta growth plan, including improved booster engines, stretched graphite epoxy solid rocket motors, extended fuel tanks, and wider payload fairings. These modifications reportedly could increase Delta's LEO payload capacity to 11,100 pounds by the mid-1990s, while a new LOX-hydrogen second stage could almost double Delta's current lift.[12]

Atlas-Centaur

The Atlas-Centaur presently has a lift capacity to LEO of about 13,300 pounds or about 5,100 pounds to geosynchronous transfer orbit. The Atlas-Centaur II is to have an ability to launch 16,150 pounds to LEO, or about 6,100 pounds to geosynchronous transfer orbit. This performance enhancement of almost 3,000 pounds to LEO is to be achieved by increasing the thrust of the booster engines 10 percent, stretching the Atlas propellant tanks 9 feet, and stretching the Centaur tanks 3 feet.

Titan

Martin Marietta has produced over 500 Titans since 1959 and will maintain active production lines well into the 1990s. A new, light-weight, graphite-epoxy Hercules solid rocket motor, which will be operational by 1990, should boost Titan IV's lift capacity to LEO from 40,000 pounds to 48,000 pounds. Improved fault-tolerant avionics have the potential to increase reliability. Although existing manufacturing facilities can produce 20 Titan cores per year, only 10 payload fairings can be produced per year with existing facilities.[13]

The Air Force currently plans to launch four Titan IVs per year from complex 41 at Cape Canaveral with a surge capability of six launches per year. Duplicating the pad 41 modifications at pad 40 at the Cape would allow eight launches per year and a surge of 12 per year.[14] Combined with 2 to 3 launches per year from the West Coast, these rates would allow the Titan IV roughly 10 launches per year, matching the Titan production rate.

CAPABILITY

Table 3-1 illustrates the net effect of proceeding with some of the enhancements described in this chapter. The result is that the United States could increase its launch capacity to about 1.4 million pounds per year to LEO, more than twice as much as the United States has ever launched in one year. The Enhanced Baseline option thus could provide a relatively low-cost means of increasing U.S. lift capabilities.

However, evolutionary enhancements to existing launch systems could not provide the low launch costs (e.g. 10 percent of current costs) sought for SDI deployment or an aggressive civilian space initiative, like a piloted mission to Mars. Furthermore, uncertainty remains about the adequacy of the resulting fleet resiliency and dependability. Unless vehicle reliabilities are improved, increasing vehicle flight rates would lead to more frequent launch failures.

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[11] Using a Delta model 6920 to reach a 150 nm circular orbit, inclined 28.5°. Delta II Spacecraft User's Manual, McDonnell Douglas Astronautics Company, Huntington Beach, CA, July 1987.

[12] Bruce Smith, "McDonnell Plans Rapid Buildup of Delta Launcher Fleet," Aviation Week and Space Technology, Feb. 16, 1987.

[13] H. Lange, Director, Special Space, McDonnell Douglas Astronautics Company, personal communication, Apr. 6, 1988.

[14] Aerospace Corporation, "Air Force-Focused Space Transportation Architecture Study," Report No. TOR-0086A(2460-01)-2, August 1987.

In addition, none of the options described in this chapter would provide redundant access to polar orbit for Titan-class payloads. This option would also not lessen the environmental impact of high launch rates unless the current generation of solid rocket boosters were replaced with clean burning solid motors or liquid boosters.

Table 3-1.—Theoretical Lift Capability of Enhanced U.S. Launch Systems

launch vehicle	mass delivered[a]	production rate[b]	launch rate[c]	capability[d]
Scout	570	12	18	6,840
Titan II	5,500	5	5	27,500
Delta II (model 8920)	11,000	12	18	132,000
Atlas/Centaur II (MLV II)	16,150	5	4	64,600
Titan III	27,600	10	4	110,400
Titan IV with new SRMs	48,000	10	10	480,000
Space Shuttle with ASRMs or LRBs	60,225[e]	n.a.	13	782,925

total = 1,600,000 pounds

x 90 percent manifesting efficiency = 1,440,000 pounds

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[a] pounds delivered to a 100 nm circular orbit at 28.5° inclination unless otherwise noted.

[b] maximum sustainable production rate with enhanced facilities in vehicles per year.

[c] maximum sustainable launch rate with enhanced facilities in vehicles per year.

[d] mass delivered times the lessor of the maximum production rate or the maximum launch rate.

[e] figure obtained by averaging the future four orbiter fleet's performance to a 150 nm circular orbit (OV102: 45,600 pounds; OV103, OV104, and OV105: 49,100 pounds), and adding 12,000 pounds of additional capacity from the ASRMs.

SOURCE: OTA.

Chapter 4

Interim Options

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Chapter 4
Interim Options

The U.S. Government's "Best Buy" is the Interim Option with . . .

1) **. . . Titan IV and more manufacturing and launch facilities** if the Nation wishes to increase U.S. launch capabilities but does not wish to incur the high development costs associated with new launch systems. Building more launch pads would also insure against launch failures that could destroy pads and limit the Nation's access to space. Resiliency concerns and limitations on available land for building more pads may make this option difficult to implement.

2) **. . . Titan V** if the Nation wants a vehicle to launch heavy payloads infrequently and wishes to limit development costs. Titan V would not be economical at high flight rates, and thus might be unsuitable for SDI deployment or a highly aggressive civilian space program.

3) **. . . Shuttle-C** if the Nation wants a new heavy lift launcher at a relatively low development cost to support the Space Station, space science payloads, polar platforms, or backup Air Force missions. Shuttle-C would not be economical at high flight rates, and thus might be unsuitable for SDI deployment or a highly aggressive civilian space program.

4) **. . . A Transition Launch System** if long-range plans indicate a need for increased launch capability by the mid to late 1990s and the Nation is willing to invest money now to lower launch costs or increase reliability to meet that demand.

INTERIM OPTION WITH TITAN IV

As one interim solution, the United States could build as many Titan IVs and Titan IV launch facilities as necessary to accomodate peak launch demand. Aggressively building new launch and manufacturing facilities would require investments of time and money comparable to those required for developing new vehicles. OTA chose the Titan IV for this option because it will have the heaviest payload capacity of all U.S. ELVs when it becomes operational.

The current Titan IV production rate is ten per year; there are two Titan IV launch pads. To meet the Expanded mission model in chapter 7 using Titan IVs would require increasing the production rate to 66 per year and building 12 additional Titan IV launch pads. Another approach would be to build fewer, high launch-rate pads, using an integrate-transfer-launch concept.[1]

Building additional launch facilities would also provide launch insurance against pad shut-downs due to launch vehicle lift-off failures. On April 18, 1986, a Titan 34D exploded shortly after liftoff raining 1.4 million pounds of debris on Vandenberg Space Launch Complex 4. Two launch pads were damaged and required almost a year to repair. Basing a space transportation strategy on an abundance of launch pads may be a good way to ensure that the Nation can maintain access to space despite the possibility of catastrophic launch failures.

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[1] U.S. Congress, Office of Technology Assessment, Reducing Launch Operations Costs: New Technologies and Practices, TM-ISC-28 (Washington, DC: U.S. Government Printing Office, August 1988), discusses various launch pad operational philosophies.

However, the Nation will face difficulties in finding sites for new launch facilities. A recent Aerospace Corporation study noted that the main problem is a lack of usable land:

> Suitable sites for processing and launching large space launch vehicles are very scarce . . . The hazards involved in overflying populated areas restrict acceptable sites to sea coast regions, the best of which are at . . . [Cape Canaveral Air Force Station, Kennedy Space Center, and Vandenberg Air Force Base]. Most of the existing launch pads were originally built in the 1950s and 1960s when environmental and social restrictions were much less severe. Satisfying the current restrictions on new construction in these environmentally sensitive areas is a complex, expensive, and time-consuming task.[2]

The study pointed out that only four suitable sites remain for constructing large launch pads at existing launch bases: two at Cape Canaveral, one at Kennedy Space Center, and one at Vandenberg. Furthermore, the sites at Kennedy Space Center and Vandenberg present difficult construction problems because of the terrain and environmental restrictions.

In response to these real estate limitations, the Rowan Companies, Inc. of Houston recently proposed developing large off-shore launch platforms based on oil rig technology. The Italians currently launch small Scout rockets from such offshore platforms. However, using such platforms for large boosters would require the resolution of a variety of technical issues such as safety and fueling at sea.[3]

A simple resiliency analysis demonstrates the problem in attempting to launch large numbers of current vehicles. Titan IV launch rates of 60 per year are inconceivable given current levels of reliability (around 95 percent) and current down times following failure (6 months). At a reliability of 1 failure in 20 flights (95 percent), 60 flights per year would result in an average of 3 failures per year. If each failure required a 6 month standdown for an investigation, the system could not approach its flight rate goal.

OTA calculations in chapter 7 indicate that this option is competitive with all other options for the Low-Growth mission model. However, it is substantially less financially attractive for the Growth or Expanded mission models. In addition, this option must be regarded as infeasible at the high launch rates implied by the Growth or Expanded mission models unless appropriate launch sites can be found and resiliency improved.

INTERIM OPTION WITH TITAN V

Titan IV will be the United States' heaviest ELV and thus would be a likely candidate for growing into a heavy lift launcher.[4] Martin Marietta, Titan's manufacturer, has identified several growth options for Titan IV. Possible modifications include enlarging the booster's core diameter, adding additional first stage liquid rocket engines and additional solid rocket motors. Table 4-1 summarizes some potential options for Titan growth.

Any version of a Titan V would require some new hardware. Enlarging the core diameter would require a new core structure; adding additional liquid rocket engines and solid rocket motors would require new thrust structures, interfaces, and analyses. In fact, transforming the Titan IV directly into a vehicle capable of placing 150,000 pounds in orbit (almost four times Titan IV's capacity) would pose systems development challenges akin to those of a brand new launch vehicle.

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[2] Aerospace Corporation, "Air Force-Focused Space Transportation Architecture Study," Report No. TOR-0086A(2460-01)-2, August 1987, p. 66.

[3] Rowan Company Briefing to OTA staff, Feb. 25, 1988.

[4] OTA has not conducted a detailed analysis of the growth potential of all existing launch vehicles. "Growing" other existing launch vehicles might have advantages. However, this subject is beyond the scope of this report.

The low-Earth orbit payload capacities of the above vehicles range from 60,000 to 150,000 pounds, almost four times the existing Titan IV's payload capacity. While going directly from the Titan IV to a 150,000 pound payload class vehicle might pose considerable technical and schedule risk, the less dramatic upgrades should have relatively predictable development costs and schedules. Martin estimates that the time required to develop a Titan V would be between 3 1/2 and 5 years depending on which growth path is taken.[5] This might permit development of a Titan-derived heavy lift launcher sooner than either a Shuttle-C or a new ELV like the Transition launch system.

The environmental effects of the large quantities of storable liquid propellants (N_2O_4/UDMH) burned by the large core engines of a Titan V could present formidable obstacles to the acceptability of the concept.[6] Although these are the same propellants used in the other Titan vehicles, shipping and handling the large quantities necessary for the Titan V, could strain current propellant technology and create environmental concerns. Furthermore, a Titan V would not be an ideal back-up for the Titan IV and its heavy payloads because of the likely technological commonality between the two vehicles. Although such technological heritage means that a new Titan would probably share the demonstrated reliability of existing Titans, it also means problems generic to the Titan family would ground the Titan V.

Cost estimates for a Titan V are not as mature as those for Shuttle-C because the Air Force is not sponsoring Titan V studies. Accordingly, the Aerospace Corporation estimated a Titan V's development cost to range from $800 million to $3.5 billion, depending on the vehicle's size.[7] In chapter 7, OTA estimated it would cost about $1.2 billion to develop Titan V. The cost analysis of chapter 7 shows that, at the high launch rates of the Expanded mission model, this option would be generally superior to Shuttle-C and Titan IV options, but inferior to the Transition launch system or the ALS. At the launch rates found in the Low Growth and Growth mission models, the Titan V is roughly competitive with all other options considered.

Table 4-1. – Titan Growth Options

Vehicle	Core Diameter	Liquid Rocket Engines	Solid Rocket Motors	Performance[a]
Titan IV	3 meters	2	2	40,000
Growth 1	4 meters	3	2 - 3	60 - 80,000
Growth 2	5 meters	4 - 5	3 - 5	80 - 130,000
Growth 3	6 meters	5 - 6	5 - 6	130 - 150,000

[a] in pounds to a 100 nautical mile orbit inclined 28.5°

SOURCE: Martin Marietta Space Launch Systems Company.

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[5] "Developments in Space Launch System Technology," Martin Marietta Denver Aerospace briefing to OTA, July 11, 1986, Washington, DC.

[6] Col. Jack Wormington, ALS Program Manager, U.S. Air Force Space Division Headquarters, Los Angeles AFS, CA.

[7] Aerospace Corporation, "Air Force-Focused Space Transportation Architecture Study," Report No. TOR-0086A(2460-01)-2, August 1987, p. 53.

INTERIM OPTION WITH SHUTTLE-C

NASA envisions Shuttle-C as a reliable, unpiloted, cargo vehicle with a 100,000 to 150,000 pound payload capability to a 220 nm, 28.5° inclination orbit. It would use the External Tank (expendable) and Solid Rocket Boosters (reusable)[8] of the current Shuttle, but replace the Orbiter with an expendable cargo carrier.[9] The cargo carrier would consist of a payload shroud, two or three Space Shuttle Main Engines (SSMEs), and a portion of the Orbital Maneuvering System, the Shuttle's on-orbit maneuvering thrusters.

NASA believes that the evolutionary nature of Shuttle-C would allow it to be developed in about four years. The major milestones include tests of cargo carrier structural loads, cargo carrier separation, vibro acoustics, and propulsion tests. Some observers feel that using Shuttle-C in the vicinity of the Space Station would require developing an automatic docking system in addition to the unpiloted cargo vehicle. However, NASA's current plans are to use the Orbital Maneuvering Vehicle (OMV) presently under development for Space Station rendezvous and proximity operations.

NASA expects Shuttle-C's reliability to be comparable to that of the Shuttle because both vehicles would employ common components. NASA sees Shuttle-C's commonality with the Shuttle as a benefit, because it would allow Shuttle-C to profit from the Shuttle's "learning curve" and avoid the "infant mortality" problems and schedule slippages normally associated with a new vehicle.[10]

The Air Force, on the other hand, has expressed concern that such commonality could be a liability because it "places all our eggs in one basket." For example, if an SSME failed and required the grounding of the Shuttle fleet, Shuttle-C would be grounded as well because it would employ the same engines. Similarly, a major accident in launch processing could ground both vehicles.

The current Shuttle-C design would place 100,000 pounds in an equatorial LEO orbit (220 nm, 28.5°), 94,000 pounds in a polar LEO orbit (160 nm), or 20,000 pounds in GEO using an existing upper stage. In addition to applications generic to all heavy lift vehicles (see box 4-1), such as launching large space science payloads, polar platforms, Shuttle-C could also serve as a test-bed for flying new Space Shuttle elements such as ASRMs, LRBs, or variants of the SSME without risking lives or a reusable orbiter. Because the Shuttle-C could carry the Centaur upper stage, it would provide alternative access to space for heavy planetary payloads, or certain national security payloads, which currently can only fly on the Titan IV.

Perhaps Shuttle-C's strongest selling point is its contribution to deployment of the Space Station. Use of Shuttle-C could reduce the time required to deploy the Space Station from 36 months to 19 months by carrying more payload per flight. It would allow compression of nineteen Shuttle flights into seven Shuttle flights plus five Shuttle-C flights.[11] Using Shuttle-C to deploy the Space Station could also increase the amount of equipment

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[8] If ASRMs were also available, Shuttle-C could use them in place of SRMs.

[9] One possibility is to recover the aft end of the cargo container, which would carry the expensive propulsion and avionics systems, by parachute.

[10] Infant mortality refers to the comparatively large number of launch vehicle failures that typically occur in the first years of operating a new launch vehicle. As flaws are discovered and corrected a launch vehicle's reliability tends to improve rapidly and then level off.

[11] A Shuttle-C could also be used in concert with a space shuttle augmented by ASRMs. In that case the payloads of the 19 shuttle flights could be compressed into 7 shuttle/ASRM flights plus 4 Shuttle-C flights. See NASA Office of Space Flight, Space Transportation for the Space Station, A NASA Report to Congress (Washington, DC, January 1988); and National Research Council, Report of the Committee on the Space Station (Washington DC: National Academy Press, September 1987), p. 22.

Box 4-1.—Heavy-Lift Launch Vehicles: Advantages and Disadvantages

Much of the debate over new launch systems has focused on the desirability of building vehicles with greatly improved lift capacity. The largest capacity vehicle now in the U.S. inventory is the Titan IV, which is designed to launch about 40,000 pounds to low-Earth orbit. The new unpiloted launch systems currently being examined—Shuttle-C, Titan V, Transition launch vehicle, and ALS—could have a lift capacity of 100,000 to 150,000 pounds to low-Earth orbit.

Advantages

A new high-capacity launch vehicle would, of course, give the United States the ability to launch large, monolithic payloads. Space Station modules, large planetary spacecraft, or SDI systems could be launched fully assembled, thereby reducing the number of required launches, assembly time, and amount of extravehicular activity, while possibly increasing reliability. Since a considerable amount of money currently is spent trying to limit the weight of even our largest payloads, increasing the capability of the launch vehicle would relax these weight constraints and help to reduce the high cost of payloads.

A heavy-lift launcher could also launch several smaller payloads at the same time, reducing the launch cost per payload and the total number of launches needed to meet program objectives. Finally, building launch vehicles with capabilities that far exceed those actually needed would allow them to be flown at less than their maximum potential. Flying launch vehicles below their maximum performance rating would lessen the strain on critical engine components and perhaps increase reliabiliy. Such excess capacity would also ease the existing burden on flight software and reduce the impact of inadvertant growth of payload weight. By carrying more payload per flight and reducing the number of flights required, a heavy lift launcher could increase the ability to fly off excess capacity and therefore increase fleet resiliency.

Disadvantages

A heavy lift launch vehicle would have some drawbacks, though. A launcher capable of delivering 150,000 pounds to orbit might be inexpensive per pound when launched fully loaded, yet this may not always be possible. At present, few monolithic payloads have been identified that could take full advantage of a heavy-lift vehicle capability. On the other hand, launching multiple payloads of small or medium-size is extremely difficult to coordinate efficiently and to insure, if the payloads are commercial. Should the United States decide to deploy a space-based ballistic missile defense system, a heavy-lift vehicle would be very efficient, since many similar payloads could be launched together to common orbits. In this respect, SDI is unique in its requirements. Commercial users and space scientists might avoid using a large "bus," with limited operational flexibility, preferring instead a dedicated "taxi" able to respond to their individual needs.

that could be integrated into the modules and checked-out on the ground, increasing both reliability of the Space Station modules, and safety of the Shuttle crews assigned to space station assembly.

A fully instrumented Space Station lab module weighs about 69,300 pounds. Launching it on the Shuttle would require off-loading 29,800 pounds of instruments and other hardware, which would be launched on additional Shuttle flights, installed, and integrated on-orbit. Shuttle-C could launch the entire 69,300 pound lab module on one flight, reducing on-orbit assembly requirements, and possibly improving the reliability of the components. Furthermore, Shuttle-C's projected 100,000 pounds of payload capacity to Space Station orbit would satisfy about 55 percent of the Station's annual resupply requirements in one flight.

NASA plans to use Shuttle-C only two or three times per year, a rate limited by the availability of the SSMEs it would use. To keep development costs down, NASA plans to use SSMEs after they have flown on the Shuttle. SSMEs are qualified for 20 Shuttle flights but NASA plans to use them at most 10 times.[12] These SSMEs would then be fully inspected, refurbished, flown, and expended on the Shuttle-C.[13] To increase Shuttle-C's flight rate beyond a few flights a year, additional SSMEs would have to be procured. This would substantially increase Shuttle-C's cost, although larger SSME production runs should produce some unit cost reduction from the present cost of $40 million per engine.

The Shuttle-C would also have a limited flight rate because, unless additional Shuttle processing facilities were constructed, it would have to be merged into the Space Shuttle processing flow. NASA estimates that Kennedy Space Center facilities would have to be modified at a cost of $20-50 million to support a combined annual Shuttle/Shuttle-C flight rate of 14 (e.g. 11 Shuttles and 3 Shuttle-Cs) without unduly disrupting Space Shuttle processing.[14] If the combined Shuttle/Shuttle-C annual flight rates approached 20, an additional Mobile Launch Platform and an SRB Stacking Facility would be needed.

NASA estimates that Shuttle-C launches would cost about the same as the current Shuttle, though it would carry roughly three times the payload. This is about $240 million per launch divided by 120,000 pounds, or about $2,000 per pound.

NASA estimates of Shuttle-C development costs range from $740 million[15] to $1.5 billion,[16] excluding the costs of facilities modifications. If this estimate is correct, Shuttle-C would pay for itself after being used for Space Station deployment alone. Station deployment using Shuttle-C would require seven fewer launches at a cost of $240 million each for a savings of $1.7 billion.

The cost analysis of chapter 7 shows Shuttle-C to be uneconomical as the Nation's principal heavy lift launcher if there is a substantial long-term demand for such capability. However, it may be an attractive option for launching the Space Station deployment or a few large science or national security spacecraft.

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[12] Letter from Dale Myers, NASA Deputy Administrator, to Robert K. Dawson, Associate Director for Natural Resources, Energy and Science, Office of Management and Budget, Jan. 20, 1988.

[13] See app. A for a discussion of how OTA treated the costing of the SSMES.

[14] Darrell R. Branscome, NASA, letter to Richard DalBello, OTA, Mar. 31, 1988.

[15] Ibid.

[16] James C. Fletcher, NASA Administrator, at hearing before the Senate Subcommittee on HUD and Independent Agencies of the Committee on Appropriations, June 8, 1988.

INTERIM OPTION WITH TRANSITION LAUNCH SYSTEM

The joint DoD-NASA Advanced Launch System (ALS) program seeks to make an order of magnitude reduction in launch costs by the late-1990s using a launch system starting from a "clean sheet of paper." Initially, the Air Force suggested that it might be prudent to build an *Interim ALS* or *Transition launch system* to meet launch demand in the mid-1990s, before the Advanced Launch System (ALS) would be operational. Such a Transition launch system would have been based primarily on existing technology. The Air Force expected to achieve a threefold reduction in operations costs. Fearing that a Transition launch system might make early deployment of space-based ballistic missile defenses more likely, Congress directed the Air Force to omit the notion of Transition launch system development from the ALS program,[17] and to concentrate instead on a program of system definition and technology development with the goal of achieving a factor of ten reduction in cost per pound.[18]

Before it was prohibited by Congress, some contractors had envisioned the Transition launch system as a modular vehicle with lift capacities ranging from 60,000 to 150,000 pounds. This range of capacity would be achieved by building a common core stage and varying the number of strap-on boosters, depending on the weight of the payload. They envisioned that a Transition launch system might therefore avoid payload coordination problems by being able to launch single or multiple payloads cost-effectively.

A precise Transition launch system cost estimate is not available because a specific design does not exist. Nevertheless, the ALS Program Director estimated that developing a Transition launch system would take about 7 years and cost about $5 billion.[19] Roughly $1 billion would be needed to develop a new engine, $2 billion for the rest of the launch vehicle, $0.5 billion for facilities construction, and $1.5 billion for ground support equipment. OTA has not had access to a detailed derivation of these cost estimates, but does not regard them as unreasonable.

Based on the estimated life-cycle cost of the particular version of the Transition launch system considered by OTA,[20] the Transition launch system appears to be one of the most cost-effective launch vehicles over the range of mission models from Low-growth to Expanded. In addition, depending on how different the Transition launch system was from today's launch vehicles, it could also provide a technologically independent, back-up means to orbit in case existing systems are grounded again because of failures.

Unlike the other three other launch systems described in this chapter, a Transition launch system would be brand new and have greater uncertainty regarding its ability to achieve goals for technical performance, schedule, cost, and flight rate. Therefore, comparisons of costs and capability between the Transition launch system and other systems must be treated with considerable caution. For that reason it may not be advisable to rely on it as a key element of another ambitious development project, such as the Space Station. NASA officials do not believe that a new launch vehicle would be initially reliable enough to launch one-of-a-kind Space Station modules.[21]

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[17] Concerns about SDI deployment prompted the Senate Appropriations Committee to include language in the Supplemental Appropriation bill funding the ALS that precluded the Air Force from further study of an Interim or Transition ALS. Senator J. Bennett Johnston (D-La) said the intent of the bill was to insure that "... the ALS design will not be sacrificed on the altar of early SDI deployment. We will proceed with the best rocket we can build using the most advanced technologies we can muster. We will not hamstring our engineers with an interim goal necessitating a hurry-up schedule for the sake of early SDI deployment." See Congressional Record, July 1, 1987, S9138.

[18] Public Law 100-180, Department of Defense Authorization Act, 1988/1989, Sec. 256 (101 Stat. 1066).

[19] Col. John Wormington, ALS Program Director, Air Force Space Division, personal communication, December 1987.

[20] The Transition launch system considered by OTA featured a proposed partially reusable unmanned launch vehicle with recoverable engines powered by liquid hydrogen and liquid oxygen.

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[21] NASA Deputy Administrator Dale Myers has informed OTA that he "absolutely flat-out rejects" using a Transition launch system for Space Station deployment, October 1987.

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Future Solutions

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Chapter 5

Future Solutions

The FUTURE SOLUTIONS option is the U.S. Government's "Best Buy" if... it wants to support a very aggressive space program that would not only develop specific launch systems but would also advance space technology. Launch systems based on emerging technologies could allow greatly reduced cost, increased performance, and operational flexibility but would entail high degrees of economic and technical risk. To obtain advanced technology launch systems by the the turn of the century, the United States must begin a sustained technology development program now.

This section examines three potential future launch systems: the Air Force's proposed unpiloted cargo vehicle, the Advanced Launch System (ALS); NASA's proposed piloted follow-on to the Space Shuttle, the Shuttle II; and the National Aerospace Plane (NASP), a piloted hypersonic vehicle that would be capable of taking off and landing like an airplane. These launch systems, particularly the Shuttle II and NASP, require more dramatic technology advances than the systems described in previous chapters. All three of these launch systems envision applying advanced technologies to vehicle design and fabrication; launch processing, integration, and check-out; mission planning and control; and if appropriate, vehicle recovery and refurbishment.

As an unpiloted cargo vehicle, the ALS would be less technically challenging than either the crew-rated Shuttle II or NASP. If aggressively funded now, ALS could be available around the end of this century. Because both Shuttle II and NASP would use highly advanced technology, and entail considerably more technical risk, they could not be operational before the early part of the next century.

These proposed vehicles would be pursued *in addition* to those vehicles already described in the Baseline or Enhanced Baseline. If the Administration and Congress decide to pursue a near-term deployment of SDI, or a piloted lunar or Mars mission, then the Nation might need the vehicles described in the Enhanced Baseline program (chapter 3) *plus* an Interim vehicle (chapter 4), *plus* one or more of the advanced vehicles described here.

Future space transportation systems will serve two broad mission categories: those requiring high mass payloads (propellants, consumables, large monolithic payloads) launched to orbit at a low cost per pound; and those using extremely high value payloads (humans or unique, expensive spacecraft), or servicing and repair, for which a low cost per flight but not necessarily low cost per pound would be desirable. An unpiloted cargo vehicle such as the ALS could probably serve the former role best. Design of the Shuttle-II and the NASP are oriented toward the latter mission type.

ADVANCED LAUNCH SYSTEM (ALS)

In undertaking the ALS, the Air Force seeks to develop a reliable, heavy-lift launch vehicle able to achieve high launch rates at low cost. ALS managers are tasked to achieve a factor of ten reduction over current costs per pound of payload orbited. The design of the ALS is also supposed to allow growth to meet changing mission requirements.[1]

In July 1987, seven contractors were each awarded $5 million, 1-year contracts by the Air Force to define conceptual designs. The Air Force asked them to include consideration of ground operations in the system designs and cost estimates and to prepare technology development plans and industrial preparedness plans. Although the details of the contractors' initial concepts are proprietary, they have considered both expendable and partially reusable vehicles (some with flyback boosters or recoverable propulsion/avionics modules), with capabilities varying from 100,000 to 200,000 pounds to LEO. Proposed engines include combinations of uprated existing engines, solid rockets, and a variety of new liquid engines.

The ALS is expected to capitalize on advanced materials and manufacturing and launch processing technologies to cut costs. For example, aluminum-lithium alloys could be used in tanks and other primary structures, which could result in 20 percent lower cost and a 10 percent increase in strength over common steel and aluminum alloys, once manufacturing and supply development is achieved. Filament-wound composite motor casings, shrouds and adapters likewise may offer cost advantages to the ALS by increasing strength and performance while reducing weight. Automation could cut the present high cost of fabricating composite structures, and robotics may be applied to plasma arc welding and other processes effectively, even in relatively low rate production. ALS managers are exploring a variety of launch operations concepts, including horizontal processing, new launch complexes and improved manufacturing, systems integration, and checkout procedures.[2]

The ALS could be a low cost per flight "space truck" capable of lifting 100,000 to 200,000 pounds to LEO, sending heavy satellites into orbit or delivering bulk supplies such as water, food, and fuel to a Space Station. The Air Force has stated that such a lift capability would primarily be required to launch elements of a ballistic missile defense system and to alleviate payload design weight constraints.[3] The Air Force estimates that the ALS could be capable of 20 to 30 flights per year after 1998.

Reliability estimates for an ALS are difficult to specify at this early phase; however, the program stresses the achievement of significantly higher reliability than current vehicles. One concept ALS contractors are investigating would incorporate an "engine-out" capability, in which the loss of one rocket engine would not endanger completion of the mission. Commercial aircraft use a similar safety feature.

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[1] As Air Force Secretary Aldridge testified before the Senate Committee on Armed Services Subcommittee on Strategic Forces and Nuclear Deterrence on March 25, 1988: "ALS will develop technologies, system design, and operational concepts for the next generation of responsive launch vehicles. These vehicles would provide the capability to meet requirements from the heaviest to the smallest payloads."

[2] See U.S. Congress, Office of Technology Assessment, Reducing Launch Operations Costs: New Technologies and Practices, OTA-TM-ISC-28 (Washington, DC: U.S. Government Printing Office, August 1988), for a more comprehensive list of technologies and management strategies for launch systems.

[3] See, for example, Star Wars at the Crossroads: The Strategic Defense Initiative After Five Years, Staff Report to Senators Bennett Johnston, Dale Bumpers, and William Proxmire, June 12, 1988.

Because development of the ALS would push the state-of-the-art in selected areas of technology, it would entail considerable cost and development risk, yet such risk would be lower than the risks involved in NASP or Shuttle II development. The aerospace field is rife with examples of technologies that took much longer to develop and implement and cost much more than originally anticipated, such as structural composites or the Shuttle's thermal protection system. Many of the goals for ALS are reminiscent of goals set in the early 1970s for the Space Shuttle regarding its lift capabilities, turnaround, and cost. The greatest impediment to the ALS program will be the high cost of developing the vehicle and building new facilities to manufacture and launch it. Historically, programs with high up-front costs and no quick return are difficult to sell. This sometimes leads to compromises in the system design that reduce the front-end costs, but also increase the operations cost. Many argue that this is what happened to the Shuttle and may be happening again to the Space Station.[4]

As mentioned in the previous chapter, another potential limitation of any heavy lifter is the difficulty of placing several different payloads, with different orbital destinations, on a single launch vehicle.[5] Maintaining a high launch rate for these vehicles may also require changing the way we presently prepare and handle payloads. For example, commonality of payload interfaces and on-pad auxiliary services may be required.

Box 5-1.—Cost Savings From New Technology

Many aerospace experts argue that significant cost savings could be achieved if time and money were spent on modernizing manufacturing facilities and on applying new technologies, some of which already exist in other industries. Yet, the application of these new technologies would increase the front-end cost, which would have to be recouped later in the program through reduced production and operations costs.

One aerospace company has estimated that automation of certain tasks could provide a 30 percent to 50 percent savings over manual processes by reducing labor and hard tooling needs. For example, Variable Polarity Plasma Arc (VPPA) welding reportedly could yield up to 70 percent savings over conventional welding and possibly eliminate the need for x-ray inspection. Computer integrated manufacturing, paperless management, modern inventory control systems, expert systems for checkout and preparation, and co-locating manufacturing and launch facilities are all being investigated for their efficacy in reducing costs and improving efficiency.

The Space Transportation Architecture Study (STAS) gave other examples of significant savings that would derive from use of various technologies. High on the list of cost-saving technologies were built-in-testing, automated data management systems, and low cost aluminum-lithium expendable cryogenic tanks.[a] Other apparently cost-effective technologies would include improved expendable tanks and structures, automatic software generation, and improved flight-management systems.[b]

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[a] Boeing Aerospace Company, "Space Transportation Architecture Study," Interim Progress Review No. 5, Apr. 7, 1987, p. 209.

[b] General Dynamics Space Systems Division, "Space Transportation Architecture Study," Special Report - Interim Study Results, vol. 2, book 3, July 10, 1987, p. 7-90, 7-91.

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[4] See, for example, John M. Logsdon, "The Space Shuttle Program: A Policy Failure?" Science, vol. 232, pp. 1099-1105.

[5] One concept for reducing operations costs is to adopt standardized mission profiles and payload interfaces, which could be possible using the ALS's "excess lift capacity." Such standardization could reduce the difficulties of launching several payloads at once.

SHUTTLE II

Shuttle II, presently the subject of limited design studies, would be a second generation Space Shuttle that could be used to service the Space Station and other future programs requiring astronauts in space. It is not seen as a heavy-lift launch vehicle. NASA envisions Shuttle II as a post-2000, piloted, two-stage fully reusable rocket-powered vehicle capable of launching between 20,000 and 65,000 pounds to low inclination LEO.

In some respects the Shuttle II is meant to be what the present Shuttle never became: a space transportation system that is relatively inexpensive, dependable, flexible, and capable of being turned around quickly. NASA planners expect Shuttle II to include light-weight primary structures, durable thermal protection systems, reusable cryogenic propellant tanks, reusable low-cost hydrocarbon and hydrogen propulsion, expert systems for decision making, robotics, and fault-tolerant, self-testing subsystems. Shuttle II could benefit from the structure and avionics advances of NASP and the production and operations advances of ALS.

As an advanced piloted vehicle, the Shuttle II could be used to support the Space Station or for self-contained experiments. NASA hopes to begin development in the mid-1990s and achieve a first flight around 2005.

Reduced launch costs would be sought by using advanced flight control systems and artificial intelligence, increasing automation, and minimizing launch and ground support. For example, one conceptual design has explored reducing ground operations costs by erecting the vehicle from a self-contained transporter after servicing it much like an aircraft. As with Soviet launch practices, there would be no need for elaborate launch towers.

As with other advanced vehicles, the primary limitations to Shuttle II are its high development cost and uncertain development timetables. Because it would carry passengers, Shuttle II's testing and certification requirements would be stringent. Also, current Shuttle II conceptual designs incorporate two high-value reusable vehicles; therefore, it would require high reliability to reduce the cost of failure. In case of failure of either reusable vehicle, standdowns could be drawn-out.

NATIONAL AEROSPACE PLANE (NASP)

The NASP program is a high-risk program with a potentially high payoff that might someday lead to a new family of aerospace vehicles[6] capable of taking off horizontally like a conventional airplane and flying all the way to Earth orbit. The principal technical hurdle is the development of a "scramjet"[7] engine capable of operating both in the atmosphere and in space. The NASP program must also solve several additional technical issues:

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[6] See for example, U.S. Congress, General Accounting Office, National Aero-Space Plane: A Technology Development and Demonstration Program to Build the X-30, GAO/NSIAD-88-122 (Washington, DC: U.S. General Accounting Office, April 1988).

[7] A scramjet is an engine in which air flows through the combustion chamber at supersonic speeds, ignites hydrogen fuel, and is expelled through the exhaust, producing thrust. Scramjets may be able to operate at speeds ranging from 4 to 25 times the speed of sound.

- Propulsion/Airframe Integration
- Aerodynamics and Computational Methods
- Materials and Structures

The joint NASA/DoD program, managed by the Air Force, is aimed at developing these critical technologies and ground testing NASP engines by 1990.[8] If the Government decides to continue the program through the design and fabrication stage, an experimental flight vehicle (the X-30) could be starting test flights in the mid to late 1990s. NASP program managers suggest that a NASP based on the results of that research could be operational by about 2010.

NASP capabilities are still uncertain, but experts assert that they will be similar to the Shuttle II. NASP's ability to take off from runways instead of large fixed launch sites and its great speed would provide unique mission flexibility and could make it useful to the military for reconnaissance or strike missions. NASP technologies may find application in civilian aircraft of the next century.

The principal uncertainties about NASP concern the feasibility of certain technologies, costs, and development and testing timeframes.[9] Although the program is designed to develop new technology as well as construct a test article, the current program emphasis on early demonstration flights could inhibit technology development. For example, the materials needed for airframe and engine components must be strong, lightweight and capable of withstanding operating temperatures of 1200°F to 1800°F while maintaining their strength. Yet the advanced metallic alloys and composites now available do not have these characteristics. Considerable research is also needed on the X-30's aerodynamic stability above Mach 15. In addition, scramjet performance at the high Mach numbers needed to reach orbit is uncertain.

Its payload capacity could be relatively small since its main function would be to transport humans for civilian space needs or military operations. Successful development thus would improve resiliency for payloads of moderate weight or piloted missions. Unresolved questions about the NASP include cost, safety, storage of cryogenic fuels, and environmental effects, including sonic booms.

Of the three advanced technology launch systems described, the NASP represents the greatest technological leap. The present X-30 research program entails considerable technological risk. It could also be a significant driver of aerospace technology development because it requires major advances in propulsion, aerodynamics, and materials. Final costs and performance of NASP technology are uncertain and will continue to be for some time. For this reason, NASP was not included in the chapter 7 mission models and funding profiles.

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[8] General Dynamics, McDonnell Douglas, and Rockwell International were each awarded $25.5 million contracts in October 1987 to continue technology development for the airframe competition. Rockwell's Rocketdyne Division and United Technologies' Pratt and Whitney Division were each awarded $85 million in September, 1987 to develop engines for the X-30.

[9] See for example David C. Morrison, "Testing the Limits at Mach 25," Science, May 20, 1988, pp. 973-975.

Box 5-2.—Unconventional Launch Technologies

Eventually launch methods may be developed that operate on physical principles other than conventional chemical propulsion. Some of these techniques would result in vast increases in launch capability. Areas of study include laser propulsion, direct launch (by cannons or coil guns), and anti-matter rockets, among others. Some "unconventional" launch methods involve extremely high accelerations. As a result, only cargo capable of tolerating high g forces could be transported. Currently most of the funding for examining the potential of these exotic technologies comes from the DOD. Although it is much too early to determine which, if any, of these concepts may become feasible, continued low-level funding support appears desirable because if even one of these concepts (or something different suggested by the research) proves useful, it could provide an inexpensive means for transporting supplies to space.

Laser Propulsion - Laser propulsion is a concept for obtaining propulsive force by beaming a laser from the ground to a launch vehicle. The laser beam would follow the craft during the entire ascent, heating a "working fluid" on the bottom of the craft. The laser pulses would produce a "laser-supported detonation" wave of hot, expanding vapor, which would produce thrust. Because the propulsive energy would come from the laser, the working fluid would be a propellant but not strictly speaking a fuel, and could be something as ordinary as reinforced ice placed beneath the payload. The routine use of lasers for propulsion would require resolving many issues, including high power levels, thruster efficiency, atmospheric propagation, beam quality, guidance and control, and environmental effects.

Ram Cannon for Cargo - A ram cannon uses a barrel filled with gaseous propellant and a projectile that flies through the propellant, igniting it like the centerbody of a ramjet engine. This reverses the usual situation as fuel is on the outside of the vehicle instead of on the inside. An experimental ram cannon has accelerated 0.1 pound projectiles at 20,000 g's to a velocity of 1.25 miles per second, about 20 percent of the velocity required to reach orbit. A full-scale ram cannon might be 2 miles long, built on the side of a mountain, and require about 50,000 tons of steel, about as much as the ocean liner Queen Elizabeth II. A ram cannon would be suitable only for payloads able to withstand extremely high accelerations. Propellants are potential payloads since they constitute more than half of current U.S. payload mass to low earth orbit.

Coilgun for Cargo - Electric catapults and guns have been studied since the 1930s, but electromagnetic devices for launching to space have been explored only relatively recently. A vertical electromagnetic coilgun in a 8 kilometer deep well might accelerate a one ton projectile to orbit under an acceleration of 1000 g's. It would require a coil to store and deliver roughly the output of a typical municipal power plant (1000 megawatts) in 90 seconds. Major questions about this technology involve energy storage costs and high technology switching systems. The impact and utilization of room-temperature superconducting material could be very significant and should be considered.

Anti-hydrogen Rocket - Anti-hydrogen has been considered for use in rocket propulsion because antimatter converts all of its mass to energy upon annihilation with normal matter. It could serve as a fuel of tremendous energy density. For example, an aerospace plane weighing 120 tons at lift-off could carry 30 tons to LEO at Shuttle-like accelerations using only 35 milligrams of anti-hydrogen and several tons of ordinary hydrogen (for use as an inert propellant).

Anti-matter, whose existence was first proven in 1932, is being made and stored today, albeit in extremely small quantities. Production of 35 milligrams of anti-hydrogen would require 19 million years at present U.S. production rates, but might be produced in five weeks in a 10 gigawatt solar-powered orbital facility, according to one estimate. One recent study stated that relatively near-term methods existed to produce and store antimatter at about $10 million per milligram.

The high energy density of anti-hydrogen poses high risks as well. Accidental annihilation of 35 milligrams of anti-hydrogen would release the energy of 3 kilotons of TNT (comparable to a worst-case Shuttle explosion) and it might produce a large electromagnetic pulse.

Chapter 6

Technology Development Options

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Chapter 6

Technology Development Options

TECHNOLOGY DEVELOPMENT is the U.S. Government's "Best Buy" if . . . it is concerned about the state of the Nation's space transportation technology base and it is optimistic about the space program's long-term prospects, but expects little near-term funding available for developing new vehicles. This option aggressively supports technology development programs across a broad range of disciplines. Greater funding for space transportation research and technology develops both technology and human capital – the next generation of aerospace engineers and technicians.

THE SPACE TRANSPORTATION TECHNOLOGY BASE TODAY

Many observers consider our existing space technology base to be inadequate. For example, since the U.S. commitment to the Space Shuttle in the 1970s, propulsion technology development has shifted from broad-based research to a very narrow focus on Space Shuttle main engine development. No other significantly advanced propulsion technologies have been developed in the United States for 20 years.[1] When the Saturn V program ended, much of the technology base was lost. Not only were the documentation of the technologies left incomplete and decentralized, but much of the "art" of certain disciplines was lost when scientists, metallurgists, and engineers left the industry or retired. In addition, many of the facilities that would be required today for developing the advanced engine technology have been closed down, mothballed, or converted to other purposes.

DEVELOPMENT OPTIONS

To reverse this deterioration, the National Research Council, for example, recommends that NASA improve engine design and develop:

- a range of advanced (low-cost, highly reliable) Earth-to-orbit engines to accommodate the potential future launch vehicle fleet mix;
- a reusable cryogenic orbital transfer vehicle (OTV) engine;
- a high-thrust, high-performance out-of-orbit propulsion system for manned Mars and similar missions; and
- a high-performance, low-thrust primary propulsion system for solar-system exploration spacecraft (nuclear-electric).

The National Research Council and other groups have also made a strong case for increasing research funding for materials and structures, automation, life support systems, and other disciplines that could contribute to a stronger technology base. Officials at NASA and DoD have recognized the need for additional attention to space transportation research and have instituted programs to help meet it.

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[1] National Research Council, Aeronautics and Space Engineering Board, Space Technology to Meet Future Needs (Washington, DC: National Academy Press, December 1987).

Box 6-1.—Experts are Concerned . . .

"Rebuilding the Nation's technology base is essential for the successful achievement of any long-term space goal. It is widely agreed that we are living off the interest of the Apollo investment, and that it is time to replenish our technology reservoir in order to enhance our range of technical options."—Sally K. Ride, *Leadership and America's Future in Space* (Washington, DC: National Aeronautics and Space Administration, August 1987).

"Many technologies critical to the future of space transportation are poised for major advances . . . Current funding levels severely inhibit the timely development of a majority of necessary key technologies . . . Facilities in the areas of propulsion, structures, and aerothermodynamics are demonstrably inadequate to cope with development testing requirements."—Joint DoD/NASA Steering Group, *National Space Transportation and Support Study*, Summary Report, May 14, 1986.

"Over the past 15 years . . . [NASA's Office of Aeronautics and Space Technology] has been severely restricted . . . NASA's preoccupation with short-term goals has left the agency with a technology base inadequate to support advanced space missions . . . [V]irtually . . . [no money] . . . has been spent on technology development for missions more than five years in the future . . . [T]he committee reviewed the state of advanced space R&T from the perspective of future missions . . . The result was depressing."—National Research Council, Aeronautics and Space Engineering Board, *Space Technology to Meet Future Needs* (Washington DC: National Academy Press, December 1987).

"Our current space technology program is deficient in two regards: first, the scope and intensity of the basic research and technology program is inadequate to provide the range of technical options we need for both the near and distant future; second, there are opportunities, now clearly indentified, which we have not developed to the stage where they can be selected for application."—*Pioneering the Space Frontier*, Report of the National Commission on Space, New York: Bantam Books, May 1986.

"Space technology advancement underlies any comprehensive future space activity. The present course is a status-quo caretaker path with no potential growth. New commitments are called for in key technologies . . . We support . . . a threefold increase in this relatively low-budget but extremely important area of space technology advancement, especially in view of strong foreign commitments to such technology development."—*U.S. Civil Space Program: An AIAA Assessment*, 1987.

FUNDING

OTA did not carry out an independent assessment of the adequacy of current funding levels for advanced technology research and development. However, several recent studies have reached the following conclusions:

National Research Council

A recent National Research Council report drew a connection between low R&D funding for space, the trade imbalance between the United States and other countries, and the loss of U.S. leadership in space.[2] Over the last 15 years, only about 2 to 3 percent of the total NASA budget has been dedicated to space research and technology, as shown in figure 6-1. The actual space R&T funding trend is given in figure 6-2. The NRC pointed out that even a comparatively mature industry like aeronautics spends about 3 percent of sales on research, while space research is running at about 1 percent of the industry's $20 billion annual space-related revenues. Because technology development for the exploration and exploitation of space is less mature than aeronautics, the report argues that space industry should have "a correspondingly greater ability to absorb usefully the technology investment." It recommends that for the next decade the NASA research and technology effort not be allowed to fall below 7 percent of the total NASA budget and that these resources should be protected from short-term requirements of major operational programs.

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[2] Ibid., pp. 153-156.

The NRC report cited rocket propulsion development as the most serious area of deficiency in the space technology base, followed by technologies supporting piloted space flight. Power, materials, and structures are next in priority with information systems, followed close behind by sensors. The report argues that the minimum funding to help improve the level of space technology would require a $530 million annual increase over the $171 million 1987 research and technology budget. The NRC's preferred program would call for a total annual increase of $970 million per year.[3] This recommended funding, which does not include NASA personnel costs, is shown in figure 6-3.

Figure 6-1.
NASA Space Research and Technology Budget as Percentage of Total NASA Budget

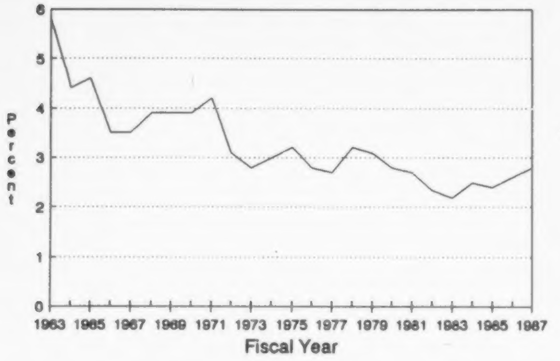


Figure 6-2.
NASA Space Research and Technology Funding

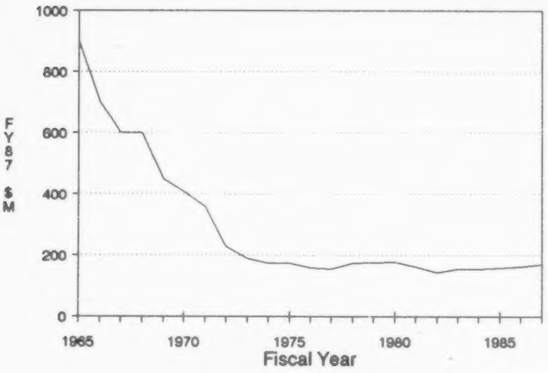
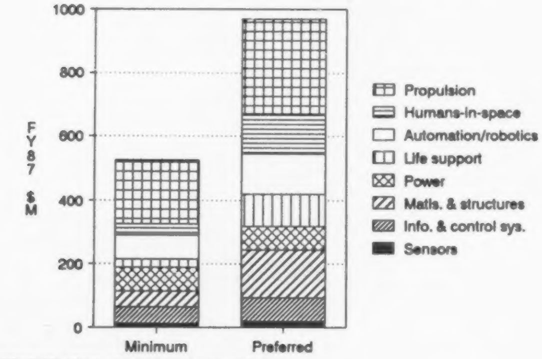


Figure 6-3.
Annual Space Research and Technology Funding Augmentation Recommended by the NRC



SOURCE: NRC, 1987 (corrected by OTA).

NASA

NASA has recognized the need to revitalize its technology base, and in 1987 began a $773.1 million, five-year Civilian Space Technology Initiative (CSTI) which has the goals of "revitalizing the Nation's civil space technology capabilities and enabling more efficient, reliable, and less costly space transportation and Earth orbit operations."[4] The CSTI consists of 10 categories of hardware development, leading to demonstrations of actual hardware. CSTI is organized into six programs within NASA's Office of Aeronautics and Space Technology. This effort is meant to reverse NASA's traditional process of using specific projects to

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[3] Ibid.

[4] NASA Office of Aeronautics and Space Technology, "CSTI Overview," April 1988.

Table 6-1.—NASA's FY89 Funding Request for the Civilian Space Technology Initiative

Propulsion	$46.7M
• Earth to orbit	
• Booster technology	
Vehicle Development	$28.0M
• Aeroassist flight experiment	
Automation and Robotics	$25.9M
• Robotics	
• Autonomous systems	
Large Structures and Control	$25.1M
• Control of flexible structures	
• Precision segmented reflectors	
Information Technology	$17.1M
• Science sensor technology	
• Data: high rate/capacity	
Power	$14.0M
• High capacity power	
Total:	$156.8M (FY88$)

SOURCE: NASA

Table 6-2.—NASA's FY89 Funding Request for the Pathfinder Program

Operations Technology	$41M
• Rendezvous and docking	
• Resource processing pilot plant	
• In-space assembly and construction	
• Cryogenic fluid depot	
• Space nuclear power	
Exploration Technology	$17M
• Planetary rover	
• Surface power	
• Optical communications	
• Sample acquisition, analysis, and preservation	
Mission Studies	$15M
Transfer Vehicle Technology	$14M
• Chemical transfer propulsion	
• Cargo vehicle propulsion	
• High energy aerobraking	
• Autonomous lander	
• Fault-tolerant systems	
Humans-in-space Technology	$13M
• Extravehicular activity/suit	
• Human performance	
• Closed-loop life support	
Total:	$100M (FY88$)

SOURCE: NASA

generate new technology. Instead of using individual high-risk projects to develop the technology needed to support specific missions, NASA now wants to first develop new generic technologies from which it can pursue projects having lower cost and technical risk.[5]

About $115 million was approved in fiscal year 1988 for this effort. An additional $156.8 million has been requested for fiscal year 1989, broken down into the six major areas (table 6-1). This requested CSTI funding would increase the share of the NASA budget going to research and technology from two percent to 2.6 percent.

NASA's technology development generally emphasizes human flight. In the fiscal year 1989 budget, NASA is also requesting $100 million to begin the new Pathfinder program,[6] which will develop technology for possible future piloted lunar and Mars missions (table 6-2). When CSTI and Pathfinder funding are combined, NASA's budget request represents $256.8 million in new technology funding, or 2.25 percent of a greatly increased NASA budget request.[7]

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[5] "NASA Will Begin $1.7 Billion Program to Revitalize Space Technology Base," Aviation Week and Space Technology, Nov. 9, 1987, p. 28.

[6] National Aeronautics and Space Administration, Office of Aeronautics and Space Technology, "Project Pathfinder, Technology Benefits Assessment," (Washington, DC: National Aeronautics and Space Administration, November 1987).

[7] NASA's proposed $11.48 billion in the fiscal year 1989 budget is a $2.46 billion increase over 1987. However, NASA's actual FY 1989 budget is anticipated to be on the order of $10.7 billion. This would probably cause concomitant budget reductions in the technology base programs.

Table 6-3.—ALS-Focused Technology Development Projects

Project[a]	Task	Applicability	Annual Cost (FY88$)
1 LOX/LH2 Engine	Complete Test/Validation Program	ELVs & STS	$17.6M
2 Propulsion Facilities	Modify Existing Test Facilities	ELVs & STS	$24.0M
3 Expendable Cryogenic Tank	Test Demonstration Tank	ELVs	$12.0M
4 Adaptive Guidance, Navigation & Control	Demonstrate Hardware/Software Integration	ELVs	$ 6.1M
5 ManTech (mfg. technology)	Full-Scale Demonstration	ELVs	$4.5M
6 Engine Definition	Preliminary Design of STME and STBE	ELVs & STS	$12.0M
7 Health Monitoring Demo	Demonstrate Integrated Technology	STS	$4.0M
8 Electromechanical Actuators	Prototype Definition	ELVs & STS	$5.5M
9 Ground Ops	Demonstrate Technologies	ELVs & STS	$15.1M
10 Solid Rocket Booster	Complete Test/Validation Program	ELVs & STS	$ 7.0M
11 NDE for SRB	Technology Demonstration	ELVs & STS	$ 1.0M
12 Precision Recovery	Advanced Controls Demonstration	ELVs	$ 2.5M
13 LOX/LHC Engine	Complete Test/Validation Program	ELVs	$32.9M
14 Booster Structures	Fabricate Demo Article	ELVs	$ 3.0M
15 Propulsion Subsystems	Test Prototypes	ELVs	$ 0.5M
16 Reusable Cryogenic Tank	Reflight Certification Program	ELVs & STS	$ 2.0M
17 Structural Certification	Complete Static and Dynamic Tests	ELVs	$ 8.0M
18 Flight Simulation Lab	Proof-of-Concept Demonstration	STS	$ 2.0M
19 Multi-Path Redund. Avionics	Test and Evaluation Definition	ELVs	$10.3M
20 Expert Systems	Ground Based Laboratory Demonstration	ELVs	$ 3.5M
21 Multi-Body Ascent CFD	Adaptive-Grid Code	STS	$ 0.5M
22 Aero Data Base	Advanced Code	STS	$ 0.5M
23 Base Heating Codes	Flowfield Models	ELVs	$ 0.5M
		Total:	$175.0M

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[a] Ranked by ALS Program Office.

ELV: Expendable Launch Vehicle.

STS: Space Transportation System (Shuttle and support systems).

SOURCE: USAF and NASA, ALS Focused Technology Program, Revision A, Mar. 1, 1988.

Table 6-4.—ALS-Focused Technology Program Funding Requested

Year	Annual Funding
1989	$155 M
1990	$210 M
1991	$173 M
1992	$127 M

Air Force

The most significant Air Force attempt to improve the technology base is the Focused Technology Program which is an integrated DoD/NASA effort funded within the ALS program. The intent of the Focused Technology Program is to highlight the technologies most relevant to ALS development. Table 6-3 lists technology development projects now in progress, showing their application to

ELVs, the Shuttle, or both. They are ranked in order of their importance to the ALS program, as assessed by the ALS program office. Table 6-4 shows anticipated annual funding requests for the ALS Focused Technology Program. Funding for each technology element is split between the Air Force and NASA budgets, with the percentage varying.

Space Transportation Architecture Study (STAS)

Perhaps the most comprehensive data available on the state of the Nation's space transportation technology base is contained in the STAS documents. The STAS effort first identified technologies that might be available by the mid-1990s and then matched the technologies with types of launch vehicles they would benefit. It developed a plan for investing in both generic and specific technologies designed "to achieve low operations cost, robustness, flexibility, and world leadership in space transportation."[8] The STAS technology plans contain recommended funding levels, milestones, system payoffs, and technology goals. The program would cost $5 to $6 billion over 10 years, with $3 to $4 billion required for the first 5 years.

National Commission on Space

The National Commission on Space stated that a space research and technology program should properly be conceived as generating future opportunities, not directed to specific applications. It did, however, emphasize some specific areas of space technology that would support the broad agenda of the National Commission on Space. These include technologies for:

- space science (e.g. sensors, propulsion);
- piloted spacecraft (e.g. life support, expert systems);
- nuclear space power (e.g. radioisotope thermoelectric generators, multi-megawatt reactors);
- space transportation (e.g. Earth-to-orbit and electric propulsion); and
- space industry (e.g. communications, remote sensing, space manufacturing).

The Commission also observed that NASA's annual funding of space research and technology fell from a high of about $900 million (constant 1986 dollars) in the mid-1960s to less than $200 million annually since the mid-1970s. The Commission recommended a tripling of NASA's technology budget from 2 percent to 6 percent of NASA's total budget, about where it was during the Apollo era.[9] Based on OMB projections of NASA's budget, over 10 years at about $10 billion per year, this amounts to a recommendation for tripling space technology funding from about $2 to $6 billion over the 10-year period.

SUMMARY

Many Government and aerospace industry officials have expressed dissatisfaction with the current space transportation technology base. Although OTA has not carried out an independent assessment of the Nation's technology requirements for space transportation, clearly many launch systems explored in this special report would require advances in several technical disciplines, including propulsion, materials, and automated manufacturing and checkout.

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[8] U.S. Department of Defense and National Aeronautics and Space Administration, Joint Steering Group, National Space Transportation and Support Study, Summary Report, May 1986, p. 22.

[9] U.S. National Commission on Space, Pioneering the Space Frontier, (New York: Bantam Books, May 1986), pp. 95-106.

As the Nation's plans for advanced space transportation research mature, it will be extremely important to maintain a balance between focused technology efforts directed towards specific applications and more long range basic research and development. Although focused research may provide important near-term results, basic research and development can provide the broad technology base that allows the Nation to capitalize on future technological opportunities, some of which are likely to be unknown today.

Chapter 7

Costs

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Chapter 7
Costs

INTRODUCTION

This chapter compares estimated life-cycle costs of using the options described in chapters 2-5 across a range of demand levels. These estimates do not include the very substantial costs of payloads and upper stages, which can be several times more costly than the vehicles that launch them.[1] These costs, as well as those of launch systems, must be reduced to foster economy, affordability, and growth of space activity.

In conducting its analysis of the costs of space transportation system hardware, facilities, and services, OTA relied initially on data and estimation methods developed by the Boeing Aerospace Company for the Space Transportation Architecture Study (STAS) and the Advanced Launch System (ALS) program. These initial estimates were adjusted to include OTA's estimate of failure costs, cost risk, and reliability. A detailed description of the cost estimation methods used to derive the figures contained in this chapter can be found in appendix A.

The cost-estimating formulae used by OTA were reviewed by NASA, the Air Force, Boeing Aerospace Company, General Dynamics, Hughes Aircraft Company, Martin Marietta Denver Aerospace, McDonnell Douglas Corporation, Rockwell International Corporation, and United Technologies Corporation. These reviewers suggested important additions and corrections, and two suggested alternative formulae for estimating the costs of developing, producing, and launching the launch vehicles considered. OTA produced alternative estimates of life-cycle cost based on the formulae proposed by two of the reviewers; the section below on "Alternative Cost Estimates," shows the ranges spanned by these formulae and the OTA estimates derived from them.

Estimates of costs of launch vehicle development and operations are necessarily uncertain because development can take longer and cost more (or less) than assumed, or demand might grow more slowly (or increase more rapidly) than assumed. For this reason, **OTA cannot assure the accuracy of the estimates contained in this chapter. However, OTA does maintain that the estimates are reasonable given the stated ground rules and assumptions, and that the methodology used here is representative of the state of the art.**

ESTIMATED COSTS OF OPTIONS

Baseline

To give the reader a basis upon which to compare the options discussed in this report, OTA defined a "Baseline" (in chapter 2). The Baseline features current vehicles launched at rates limited only by the constraints imposed by existing manufacturing and ground facilities. Limiting the Baseline to existing facilities means that it could not even fly all the missions in the Low-Growth mission model. Although the Baseline might

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[1] Some spacecraft cost several hundred thousand dollars per pound; see Space Systems and Operations Cost Reduction and Cost Credibility Workshop, Executive Summary (Washington, DC: National Security Industrial Association, 1987), fig. 3.7.3.

Box 7-1.—Cost Components

Life-cycle cost—appropriately discounted to reflect risk and opportunity cost—is the most important economic criterion by which to compare different launch vehicle architectures. For each mission model examined here, the option that has the lowest discounted life-cycle cost would be most economical, if the assumed discount rate were appropriate and if the required funding were available. However, the most economical launch architecture might be deemed unaffordable if it would require more spending in a particular year than the Executive would budget or than Congress would authorize and appropriate for the purpose. To help the reader compare the long- and short-term advantages of the various options, this chapter displays their funding profiles for each mission model in constant 1988 dollars. Funding profiles in current ("then-year") dollars are exhibited in appendix B.

Life-cycle costs include both non-recurring and recurring costs. The non-recurring costs include costs of design, development, testing, and evaluation (DDT&E), production of reusable vehicle systems, and construction and equipping of facilities. The recurring costs include all costs of planned operations, including production of expendable vehicle systems, as well as expected costs of failures. Expected costs of failures are calculated from estimates of vehicle reliabilities and estimates of the costs that would be incurred in the event of a failure (see box 7-2, **"Failure Costs,"** and appendix A).

In general, early non-recurring investment is required to reduce total discounted life-cycle cost. Trade-offs between investment and savings are discussed below in the section, **"Trade-Offs between 'Up-Front' and 'Out-Year' Costs."**

Cost risk is included in some of the cost estimates quoted here. Cost risk was defined in the Space Transportation Architecture Study (STAS) as a subjectively estimated percentage increase in life-cycle cost (discounted at 5 percent) that the estimator expects would be exceeded with a probability of 30 percent, assuming certain groundrules are met. Basically, cost risk is intended to represent likely increases in life-cycle cost caused by unforeseen difficulties in technology development, facility construction, etc. However, cost risk as defined in the STAS does not include risks of cost growth due to mission cancellations, funding stretch-outs, or standdowns after failure, which were excluded by the groundrules of the study. The cost risk estimates by OTA also exclude risks of mission cancellations, funding stretch-outs, and standdowns after failures; estimation of these risks in a logically consistent manner will require more sophisticated methods than were used here, or in the STAS. However, OTA's cost risk estimates **do** include the risk of greater-than-expected failure costs (see box 7-2, **"Failure Costs,"**).

Because cost risk is defined in terms of life-cycle cost and not annual cost, cost risk is excluded from the funding profiles in this chapter but included in the histograms comparing life-cycle cost. Cost risk is also excluded from the estimates of savings on page 75, because all options use common vehicles (Shuttle, Titan IV, and MLV) and facilities, and their cost overruns (if any) may be correlated. OTA has not attempted to estimate these correlations and their resultant savings in cost risk.

be adequate for the near-term—representing growth from 1985 launch rates in all categories (piloted, light cargo, and heavy cargo)—29 of 161 post-1999 heavy cargo missions in the Low-Growth mission model would have to be cancelled. Because Baseline vehicles and facilities cannot launch all the missions in the Low-Growth mission model, its life-cycle cost for doing so cannot be calculated.

Enhanced Baseline Option

The Enhanced Baseline Option features an improved Shuttle with advanced solid rocket motors (ASRMs), improved Titan IVs with new solid rocket motors and fault-tolerant avionics, MLVs, and an extra Titan IV pad to handle the peak Titan IV launch rate in the Low-Growth mission model (16 per year).

Box 7-2.—Failure Costs

Expected launch vehicle failure costs are the product of the expected failure frequency (calculated from vehicle reliability estimates) and the estimated failure cost per vehicle (based on historical experience). Cost per failure will generally include cost of accident investigation and corrective action. It may include costs of replacing and reflying lost payloads, replacing reusable vehicle components, and delays pending completion of accident investigation.

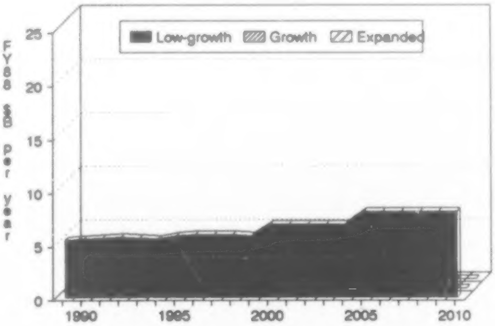
In the Space Transportation Architecture Study (STAS), operations costs were estimated assuming that operations would be continuous (i.e. no "standdowns"), and failure costs were estimated assuming that all lost payloads would be replaced and reflown. The same assumptions were made in this report. Accident investigation costs were included, *but launch operations were not assumed to be suspended* pending their completion. To assume that a fleet would stand down pending completion of accident investigation requires that the opportunity costs of delaying missions be estimated. Moreover, since some missions would be cancelled as a result of the delay, life-cycle costs would have to exclude missions not flown.

In addition to calculating expected failure costs, OTA has estimated the expected statistical variations in failure costs. One measure of such variations is the standard deviation of failure costs. A related measure, 1.9 times the standard deviation, is the difference between the expected failure cost and the 70th percentile of failure cost, i.e. the excess failure cost which would be exceeded with a probability of only 30 percent. This excess failure cost has been included in OTA's estimates of cost risk, along with the cost risk as defined in the STAS. For a more detailed discussion of the cost estimation methodology employed in this report, see appendix A.

Enhanced Baseline Option costs are estimated only for the Low-Growth mission model. To fly all missions in the Growth mission model, which has a peak Titan IV launch rate of 30 per year, would require about five new Titan IV pads. As noted in chapter 3, about 14 new Titan IV pads would be needed to launch 66 Titan IVs per year in the Expanded mission model. Because existing launch sites could accommodate at most four new Titan IV pads,[2] and construction of the facilities infrastructure for an additional ten pads would represent a radical rather than incremental change in launch facilities and operations, we assume that the Enhanced Baseline Option—conceived as an evolutionary enhancement—could not accomodate Growth or Expanded peak launch rates.

Figure 7-1 shows the estimated funding profile in 1988 dollars for the Enhanced Baseline Option sized for the Low-Growth mission model. The funding profile is relatively flat. Forty to fifty percent of the annual expenditure is for failure costs; about half of the rest ($1.3B per year) is the fixed cost of improved Shuttle operations.[3] The second largest contributor is the incremental cost of improved Titan IV launches ($95M per launch). The fixed cost of Titan IV operations and the incremental cost of improved Shuttle launches are relatively small. There

Figure 7-1.—Funding Profile for Enhanced Baseline Option



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[2] This includes one launch pad at Vandenberg Air Force Base, one at Cape Canaveral Air Force Station, and two at Kennedy Space Center.

[3] Annual operations costs have a variable component, which depends on the number of launches during the year, and a fixed component, which does not. In this special report, total (fixed plus variable) annual operations costs are defined as recurring costs.

is a barely noticeable hump of development and facility construction costs in the early 1990s. Because fixed costs are such a large fraction of total annual costs, total annual costs increase only about 50 percent as the combined-fleet launch rate doubles between 1989 and 2010.

The funding profile for the Enhanced Baseline Option—and all other options discussed in this chapter—includes expected failure costs but not cost risk. The analysis assumes that operations would continue after failures. Appendix A describes the cost estimation methodology and other assumptions in greater detail.

Table 7-1.—Cost Summary—Enhanced Baseline Option

Life-cycle cost in FY88 $B	
- discounted 5% per year:	$83B
- undiscounted:	$150B
Peak funding rate and year	
- in FY88 $	$8B in 2005
- in current $	$21B in 2010

Interim Option with Titan IV

The Interim Option with Titan IV assumes that the United States could build as many new Titan IV launch facilities as are necessary to accomodate the peak launch rate for each mission model. Note that here, and in the options that follow, OTA has named the option according to the largest cargo system in the option. Although each option actually supports a mixed fleet of vehicles, this option, for example, includes existing facilities and launch vehicles that are now operational or in production (the Shuttle, Titan IVs with new solid rocket motors, and MLVs).

Figure 7-2 shows estimated funding profiles for this option for all three OTA mission models. The funding profile for the Low-Growth mission model is relatively flat, with expected failure costs consuming almost half the annual expenditures, and with fixed costs of Shuttle operations taking up almost half of the remainder. The second largest contributor is the incremental cost of Titan IV launches ($100M per launch). The fixed cost of Titan IV operations and the incremental cost of Shuttle launches are relatively small. There is a barely noticeable hump of facility construction costs for the Low-Growth model, and greater increases in the Growth and Expanded mission models, but no development costs. As in the Enhanced Baseline Option, fixed costs are a large fraction of total annual costs, therefore total annual costs hardly change as the combined-fleet launch rate doubles between 1989 and 2010 in the Low-Growth mission model and only double as the launch rate more than quadruples—and as the heavy cargo launch rate increases tenfold—in the Expanded Mission Model.

This option assumes that additional on-shore or off-shore Titan IV launch sites can be found that are acceptable in terms of safety, security, and environmental impacts and risks, and that these pads can be built at a cost comparable to the cost of new Titan IV pads at Vandenberg Air Force Base or Kennedy Space Center. This assumption is most critical for the Expanded mission model,

Figure 7-2.—Funding Profiles for Interim Option with Titan IV

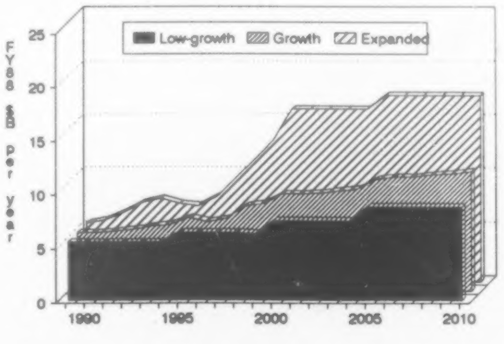

Table 7-2. – Cost Summary – Interim Option with Titan IV

	mission model		
Life-cycle cost (1989-2010) in FY88 $B	Low Growth	Growth	Expanded
- discounted 5% per year:	$87B	$100B	$150B
- undiscounted:	$150B	$180B	$270B
Peak funding rate and year			
- in FY88 $ per year	$8.7B in 2005	$11B in 2010	$17B in 2005
- in current $ per year	$22B in 2010	$29B in 2010	$45B in 2010

which will require the most new sites. OTA has not examined the reasonableness of these assumptions,[4] but, as mentioned in the Enhanced Baseline Option, we note that there is little room at Vandenberg for expansion.

Interim Option with Titan V

The Interim Option with Titan V features the Titan V – a proposed heavy-lift (100,000-pound class) launch vehicle derived from the Titan IV; it also includes unimproved Shuttles, MLVs, unimproved Titan IVs (until Titan Vs became operational in 1996), and additional launch facilities as required to fly all missions.

Figure 7-3 shows the estimated funding profiles for the Interim Option with Titan V in the Low-Growth, Growth, and Expanded mission models, in fiscal year 1988 dollars. The investment costs are comparable to those of the Interim Option with Titan IV. Titan Vs could use converted Titan IV pads. This analysis assumes that for $500M all Titan IV pads could be modified to launch Titan Vs at a maximum annual launch rate of 12 per year, the assumed current maximum annual Titan IV launch rate.

The out-year costs, also comparable to those of the Interim Option with Titan IV, are attributable largely to the incremental cost of

Figure 7-3. – Funding Profiles for Interim Option with Titan V

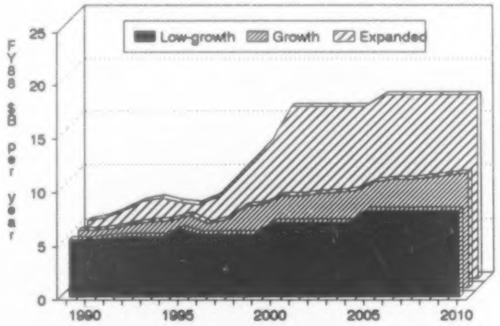

Table 7-3. – Cost Summary – Interim Option with Titan V

	mission model		
Life-cycle cost (1989-2010) in FY88 $B	Low Growth	Growth	Expanded
- discounted 5% per year:	$85B	$98B	$140B
- undiscounted:	$150B	$180B	$270B
Peak funding rate			
- in FY88 $ per year	$8.1B in 2005	$11B in 2010	$17B in 2005
- in current $ per year	$21B in 2010	$27B in 2010	$44B in 2010

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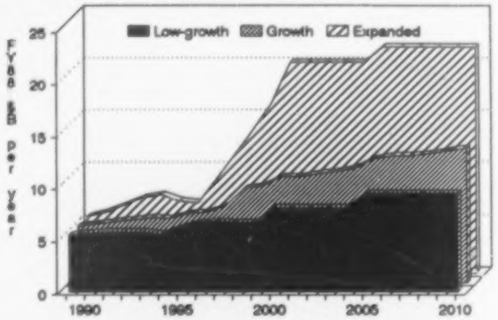
[4] It should be noted that off-shore options might require additional infrastructure to handle hazardous fuels or provide transportation to an off-shore location.

Titan V launches, which is estimated as $160M per launch – 60 percent greater than that of Titan IV, although 20 percent fewer launches would be required to fly payloads off-loaded from Titan IVs. The fixed annual cost of Titan V launches is also estimated to be substantial – about $270M per year, as compared to $200M per year for Titan IV.

Interim Option with Shuttle-C

The Interim Option with Shuttle-C features the expendable Shuttle-C cargo vehicle proposed by NASA and includes unimproved Shuttles, MLVs, unimproved Titan IVs (until Shuttle-C is operational in 1995), and additional launch facilities as required to fly all missions. Figure 7-4 shows the estimated funding profiles for the Interim Option with Shuttle-C in the Low-Growth, Growth, and Expanded mission models, in 1988 dollars.

Figure 7-4. – Funding Profiles for Interim Option with Shuttle-C



These profiles show a modest early hump of investment in Shuttle-C development – $1.2B over 6 years – and construction of additional Shuttle pads, which Shuttle-C could use with minimal modification (not costed here). They also show high annual costs in the out-years, especially at high cargo launch rates. The high annual out-year cost is attributable primarily to the high estimated incremental operations cost of Shuttle-C: about $235M per launch, less savings realized by using depreciated Space Shuttle Main Engines (SSMEs), which NASA will no longer fly on the Shuttle.[5] By replacing Titan IV, Shuttle-C launches would outnumber Shuttle launches in all the mission models, so savings from flying depreciated SSMEs would be small.[6] In the out-years of OTA's mission models, the estimated incremental cost per Shuttle-C flight would exceed fourfold that of Shuttle, twice that of Titan IV, and sevenfold

Table 7-4. – Cost Summary – Interim Option with Shuttle-C

	mission model		
Life-cycle cost (1989-2010) in FY88 $B	Low Growth	Growth	Expanded
- discounted 5% per year:	$92B	$110B	$170B
- undiscounted:	$160B	$200B	$330B
Peak funding rate			
- in FY88 $ per year	$9.4B in 2005	$13B in 2010	$22B in 2005
- in current $ per year	$24B in 2010	$33B in 2010	$55B in 2010

---

[5] A new SSME costs about $40 million. Boeing assumed that SSME lifetime on the Shuttle would increase from 10 flights (ca. 1985) to 20 flights (1989-1995), and 40 flights (post-1995). Based on this assumption, Boeing estimated that the equivalent of four fully depreciated SSMEs would be available in 1989, when the OTA mission models begin. NASA has assumed a 10-flight lifetime. Assuming a shorter engine life reduces the estimated cost per Shuttle-C flight; this should be reflected in higher cost per Shuttle flight. The actual cost difference resulting from the diverging assumptions is not great (see appendix A).

[6] The SSME credit would be only $2M per flight in the out-years of the Low-Growth mission model, or $0.5M in the out-years of the Expanded mission model.

Box 7-3.—Shuttle-C Low-Launch-Rate Option

At only three launches a year, Shuttle-C could simplify and improve Space Station assembly by launching outfitted Space Station modules too heavy for the Shuttle or Titan IVs to carry. It could provide redundant means of launching heavy cargo and hence increase operational flexibility. OTA has estimated the costs of using Shuttle-C for only three launches a year after 1994, and using Titan IVs and the Shuttle fleet for other traffic. OTA assumed that in each year after 1994:

- Shuttle-C would replace the Shuttle on 20 percent of the Shuttle flights in the [non-HLLV] mission models.
- The remaining Shuttle-C flights (0.6-1.4 per year) would carry cargo offloaded from Titan IVs; four Shuttle-C flights would replace five Titan IV flights.
- MLV flights would be reduced by 30 percent of the heavy cargo vehicle flights in the mission model which are flown by Shuttle-C (i.e., not counting the flights on which Shuttle-C substitutes for the Shuttle).

This option would require more investment than would the Titan IV or Shuttle-C options, because both a Shuttle-C and another cargo vehicle would be needed. However, it would have essentially the same discounted life-cycle cost—no more than about 1 percent greater in any mission model. Hence although Shuttle-C would not be cost-effective as the primary U.S. heavy-lift launch vehicle, it could provide useful flexibility—especially for selected NASA missions—at a small premium in life-cycle cost.

Cost Summary

Life-cycle cost in FY88 $	Low Growth	Growth	Expanded
- discounted 5% per year:	$87B	$100B	$150B
- undiscounted:	$150B	$180B	$280B
Peak funding rate			
- in FY88 $ per year	$8.2B in 2005	$10B in 2010	$16B in 2005
- in current $ per year	$21B in 2010	$27B in 2010	$42B in 2010
Comparison with Titan IV			
- extra nonrecurring cost	$860M	$900M	$900M
- extra life-cycle cost	$460M	$690M	$1.7B

that of the Advanced Launch System.[7] Most of the costs are not engine-related; they include the costs of the payload module ($55M, including payload cradles), the boattail in which the engines are mounted ($55M), and other parts ($56M, including an external tank). No costs of using, recovering, and refurbishing Orbital Maneuvering Vehicles (OMVs) for docking Shuttle-C to the Space Station are included.

In this option, Shuttle-C is assumed to be the Nation's primary heavy cargo vehicle; this contrasts with NASA's proposal that Shuttle-C be used only for a few selected missions, such as Space Station deployment. NASA concedes that an expendable Shuttle-C would not be economical at high launch rates; partially reusable versions, which have been considered by NASA and the Air Force, might be. The box "Shuttle-C Low-Launch-Rate Option" estimates costs for an option in which Titan IVs would launch most heavy cargo, and Shuttle-C would be launched only three times per year beginning in 1995. This option is less expensive than the Interim Option with Shuttle-C and competitive with the Interim Option with Titan IV. At essentially the same life-cycle cost of the Titan IV option, Shuttle-C could simplify Space Station assembly by launching outfitted Space Station modules too heavy for the Shuttle or Titan IVs to carry. **Hence Shuttle-C appears economical for selected missions (i.e, Space Station module launches) but does not compare well as the principal U.S. heavy-lift launch vehicle.**

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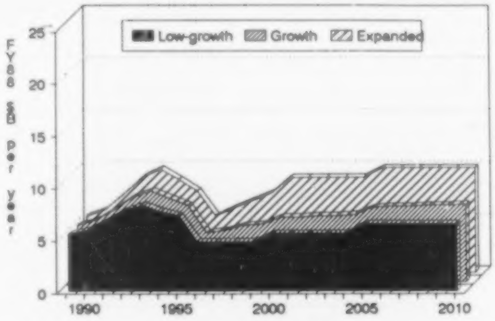
[7] See appendix A.

Interim Option with Transition Launch Vehicle

The Interim Option with Transition Launch Vehicle features a proposed partially reusable unpiloted launch vehicle with recoverable engines that burn liquid hydrogen and oxygen; for reliability, it uses no solid-fuel engines. The option also includes unimproved Shuttles, MLVs, unimproved Titan IVs (until they are superseded by Transition vehicles in 1996), and additional launch facilities as required to fly all missions. Figure 7-5 shows the estimated funding profiles for the Interim Option with Transition Launch Vehicle in the Low-Growth, Growth, and Expanded mission models, in 1988 dollars.

Figure 7-5. – Funding Profiles for Interim Option with Transition Launch Vehicle



These profiles show higher and longer investment humps than for Shuttle-C, but very little growth in out-year costs, even while launch rates double (in the Low-Growth mission model) or more than quadruple (in the Expanded mission model). Although the initial investment is greater for this launch option, its life-cycle cost is relatively low. Average launch cost (life-cycle cost divided by total number of launches) is especially low at high launch rates, because it is assumed that the early investment has resulted in very low incremental costs ($54 M) for launches.

Advanced Option with Advanced Launch System

This option features the Advanced Launch System design proposed by Boeing Aerospace Company for launching large cargo payloads economically at high launch rates. It also includes the Shuttle, MLVs,

Table 7-5. – Cost Summary – Interim Option with Transition Launch Vehicle

	mission model		
Life-cycle cost (1989-2010) in FY88 $B	Low Growth	Growth	Expanded
- discounted 5% per year:	$81B	$87B	$110B
- undiscounted:	$130B	$150B	$190B
Peak funding rate			
- in FY88 $ per year	$8.2B in 1993	$8.7B in 1993	$10B in 2005
- in current $ per year	$16B in 2010	$19B in 2010	$26B in 2010

unimproved Titan IVs (until replaced by the Advanced Launch System in 2000[8]), and additional launch facilities as required to fly all missions.

The Advanced Launch System program has not yet selected a vehicle design, but designs currently under consideration include vehicles capable of launching payloads substantially heavier than 50,000 pounds. The cost estimates quoted in this section refer to a partially reusable vehicle featuring a flyback booster burning liquid oxygen and hydrocarbon propellants; a core stage with expendable tanks and payload fairing; and a recoverable payload/avionics module with engines that burn liquid oxygen and hydrogen. OTA's selection of this vehicle for purposes of cost estimation should not be construed as an endorsement of this particular configuration. OTA did not examine all proposed vehicles.

Figure 7-6 shows the estimated funding profiles for the Advanced Option with Advanced Launch System in the Low-Growth, Growth, and Expanded mission models. These profiles show substantial investment humps even for the Low-Growth mission model, but low out-year costs that grow little with increasing heavy cargo traffic. Compared to the Shuttle II option, the Advanced Launch System option is much more economical because its new vehicle is optimized for carrying heavy cargo to orbit, not for piloted sorties or return of cargo.

This analysis makes the key assumption that the incremental cost of ALS operations will be $33M per launch—much lower than that of Titan V ($160M) or Shuttle-C (about $235M), and just under 1/3 that of Titan IV ($100M). The ALS program is required by law[9] to seek to lower recurring launch cost per pound by a factor of ten compared to current ELV launch costs, which were assumed to be about $3000 per pound to low-Earth orbit in 1987 dollars. An ALS launch vehicle must be able to lift 110,000 pounds to low-Earth orbit to fulfill this goal, if its incremen-

Figure 7-6.—Funding Profiles for Advanced Option with Advanced Launch System

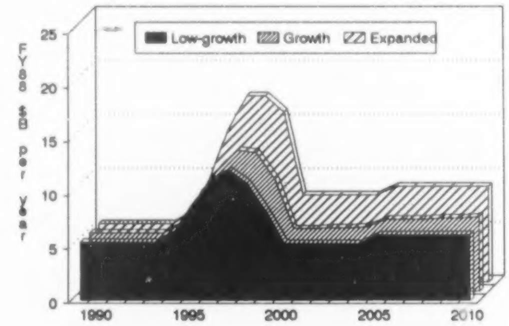


Table 7-6.—Cost Summary—Advanced Option with Advanced Launch System

	mission model		
Life-cycle cost (1989-2010) in FY88 $B	Low Growth	Growth	Expanded
- discounted 5% per year:	$89B	$95B	$120B
- undiscounted:	$150B	$160B	$200B
Peak funding rate			
- in FY88 $ per year	$11B in 1997	$12B in 1998	$16B in 1998
- in current $ per year	$17B in 1997	$19B in 1998	$24B in 1999

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[8] Boeing assumed an initial launch capability of 1996; OTA considers 2000 more plausible. A sensitivity analysis indicates that the rank order of option costs is insensitive to the change.

[9] Public Law 100-180, Department of Defense Authorization Act, 1988/1989, Sec. 256 (101 Stat. 1066).

tal launch cost is $33M per launch. However, it is unclear that there would be many payloads or feasible combinations of payloads that large. As a result, actual cost savings could be much smaller than the theoretical maximum savings.

The uncertainties in estimates of Advanced Launch System costs are particularly high because of the uncertainty about which vehicle configuration would be selected. To indicate the impact of selecting a different configuration on the cost of this option, OTA also estimated the cost of an Advanced Launch System featuring an expendable launch vehicle with a lower development cost, no cost of procuring reusable elements, a lower fixed annual operations cost, but a higher incremental cost per launch. OTA assumed this option would be available earlier (1996 v. 2000) at lower cost risk. Its payload deployment reliability is estimated to be slightly lower, but it need not be recovered and therefore has no risk of failure during recovery. This and other cost estimates, are discussed in the section on "Alternative Cost Estimates."

Advanced Option with Shuttle II

The Advanced Option with Shuttle II features a proposed fully reusable piloted launch vehicle derived from the current Shuttle. Although Shuttle II is not a firm concept, this analysis assumes that it can carry payloads comparable to those carried by the Shuttle and that it will replace the Shuttle in the year 2000. This option also includes unimproved Titan IVs, MLVs, and additional launch facilities as required to fly all missions.

Figure 7-7 shows the estimated funding profiles for the Advanced Option with Shuttle II in the Low-Growth, Growth, and Expanded mission models. Each profile shows a prominent hump of spending for Shuttle II development and facilities from 1994 to 1999. These calculations assume that expenditures for Shuttle II development and facility construction would be delayed until 1994 and completed in 1999 so that Shuttle II could be launched in 2000. Shuttle II could use converted rather than new pads. This analysis assumes that for $1B all Shuttle pads could be modified to launch Shuttle II vehicles at a

Figure 7-7. — Funding Profiles for Advanced Option with Shuttle II

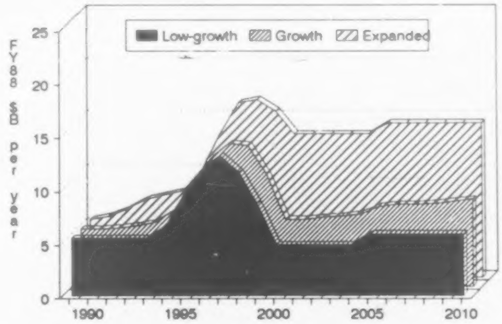

Table 7-7. — Cost Summary — Advanced Option with Shuttle II

	mission model		
Life-cycle cost (1989-2010) in FY88 $B	Low Growth	Growth	Expanded
- discounted 5% per year:	$89B	$100B	$150B
- undiscounted:	$150B	$170B	$270B
Peak funding rate			
- in FY88 $ per year	$13B in 1997	$13B in 1997	$17B in 1998
- in current $ per year	$19B in 1997	$21B in 2010	$37B in 2010

maximum combined annual launch rate of 16 per year, the maximum Shuttle launch rate sustainable with current facilities, in Boeing's estimate.[10] The profiles for the Growth and Expanded mission models show smaller humps of earlier spending (1989-1994) for Titan IV launch facilities.

Compared to the Interim Options with Titan IV or Titan V, the out-year costs of the Shuttle II option are lower, because the fixed annual operations cost of Shuttle II would be much lower than that of the Shuttle, which it would replace, and the expected failure cost of Shuttle II would be lower because it is expected to be more reliable than the Shuttle. Annual operations cost would be reduced by the same amount in all three mission models, because the mission models differ only in launch rates for heavy cargo vehicles.

Although OTA's analysis assumes Shuttle II to be much more economical than the current Shuttle, the Advanced Option with Shuttle II would not be as economical as other options, because of the predominance of cargo traffic in OTA's mission models. Only the Shuttle-C option would be more expensive. If demand for piloted flights were to increase and demand for cargo launch were to decrease, the Advanced Option with Shuttle II could become more economical than the other options considered here. In any case, **sometime early in the next century, the current Shuttle will begin to exceed its useful lifetime or will become obsolete. At this point, a replacement for the current Shuttle will be necessary whether or not it is competitive at launching cargo with then existing or planned cargo vehicles.**

COMPARISONS

Cost Comparison

The histogram in Figure 7-8 compares the expected life-cycle cost and cost risk of each option in 1988 dollars discounted at 5 percent, for the Low-Growth mission model. The bottom portion of each bar represents the expected life-cycle cost, excluding failure costs. The middle portion of each bar represents the expected cost of failures. The top portion of each bar represents the cost risk.[11] The figure shows that at Low-Growth launch rates, no option promises savings with confidence, and that cost is relatively insensitive to choice of option. Figures 7-9 and 7-10 are similar comparisons for the Growth and Expanded mission models, respectively. Figure 7-10 shows that in the Expanded mission model, clear-cut savings are possible with some options, while other options would be wasteful. That is, cost is more sensitive to choice of option at Expanded launch rates than at Low-Growth launch rates.

Figure 7-11 is a superposition of figures 7-8, 7-9, and 7-10, showing the sensitivities of cost to mission model as well as to choice of option.

These cost comparisons suggest the following conclusions:

- **Low Growth:** If the future U.S. space program resembles the Low-Growth mission model considered here, then it is not possible to distinguish meaningfully among the options examined. Uncertainties of cost estimation obscure the small estimated differences in savings be-

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[10] NASA estimates a maximum sustainable Shuttle launch rate of 14 per year; OTA's mission models assume no more than 12 Shuttle flights per year.

[11] The cost risk in dollars is the cost risk in percent, divided by 100, times the expected cost of the option.

Figure 7-8.—Cost Comparison—Low-Growth Mission Model

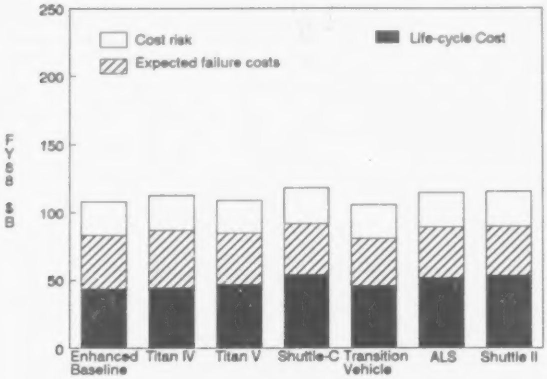


Figure 7-9.—Cost Comparison—Growth Mission Model

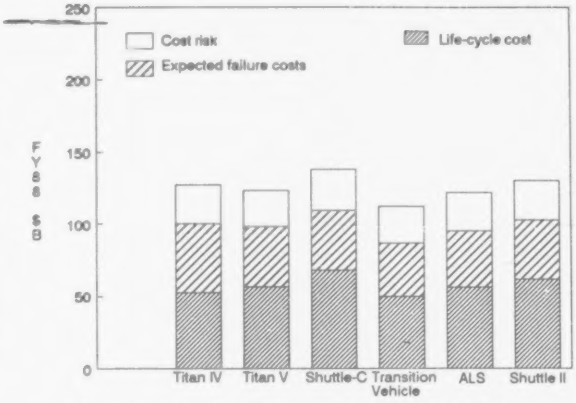


Figure 7-10.—Cost Comparison—Expanded Mission Model

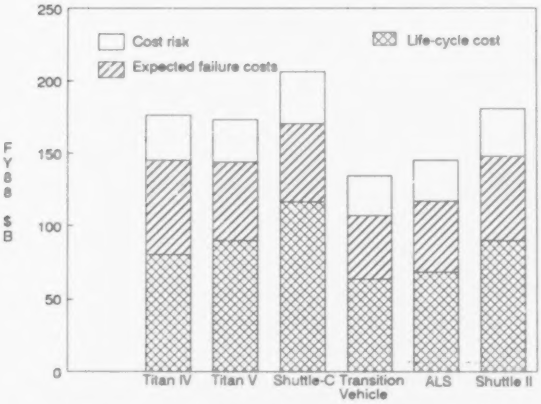
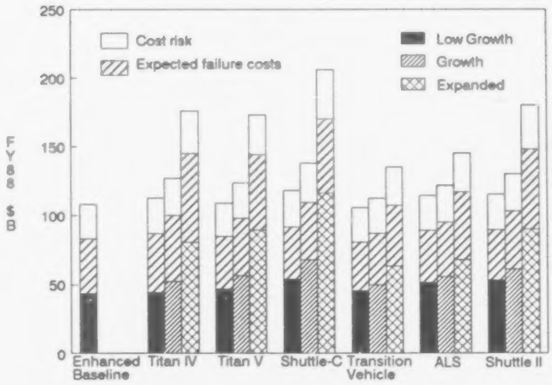


Figure 7-11.—Cost Comparison—All Mission Models



tween the options. In short, at Low-Growth launch rates, life-cycle cost is insensitive to choice of option and is unlikely to be reduced significantly by any option OTA considered. Development of a new cargo vehicle would, however, present an opportunity to increase the reliability of cargo delivery.[12] This would also increase the operational availability and resiliency of launch systems without requiring that downtimes after failures be reduced. It would increase the probability of access to space and hedge against a greater than expected growth in launch demand in the late 1990s. If continuation of piloted spaceflight were of paramount importance, a Shuttle II might be appropriate.

- **Growth:** If the U.S. space program expands to resemble the Growth mission model, then Transition Launch Vehicles would seem to be the best choice. The other options—except use of Shuttle-C as the primary cargo vehicle—would be economically competitive, though here again estimated differences in savings are obscured by uncertainties of cost estimation. The Transition Launch Vehicle or Advanced Launch System options could maximize the reliability of cargo delivery.

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[12] Increases in reliability are limited by probabilities of human error and catastrophic component failures not avoidable through redundancy.

- **Expanded:** For a greatly expanded launch demand, the Transition Launch Vehicle option or an Advanced Launch System would be appropriate. These options have the lowest estimated life-cycle costs, and their primary cargo vehicles are intended to provide greater reliability of cargo delivery.

Trade-Offs Between "Up-Front" and "Out-Year" Costs

In addition to choosing which technologies and launch vehicles to pursue, Congress must also determine the most appropriate plan for funding these capabilities. Much has been written about how restrictions on the "up-front" Shuttle development costs resulted in the current high operations costs.[13] The Administration and the Congress now face similar trade-offs between reducing the up-front costs of developing the next generation of launch vehicles and facilities reducing the "run out" costs of operating them. One way to illustrate the trade-offs available is to show the potential savings, relative to that of a reference option, obtainable by investing in development, facility construction, and fleet procurement for the other options. For each mission model, table 7-8 shows the expected investment required to fly all missions with each option and the expected potential savings in discounted life-cycle cost relative to the Interim Option with Titan IV. Cost risk is not included in the calculation of life-cycle costs.[14]

The table shows that at Low-Growth traffic levels, the Transition Vehicle, Enhanced Baseline, and Titan V options are expected to yield savings that are at most a small fraction of the cost risk of each option. The Enhanced Baseline Option is expected to have the greatest cost leverage (savings to investment ratio). Some options would require greater investment *and* save less money, if any. At traffic levels reflective of the Growth model, the Transition Vehicle, Titan V, and Advanced Launch System options are all expected to yield savings. At the high cargo launch rates of the Expanded mission model, the Titan V, Transition Vehicle, and Advanced Launch System options are expected to yield savings. Because estimates of cost and savings are both quite uncertain, small differences in the estimates should not be regarded as meaningful.

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[13] See, for example, John Logsdon, "The Decision to Develop the Space Shuttle," Science, vol. 232, May 1986, pp. 1099-1105; NASA, Technology Influence on Space Shuttle Development (Houston, TX: NASA JSC, June 8, 1986); and Boeing Aerospace Operations, Shuttle Ground Operations Efficiencies/Technologies Study, May 4, 1987.

[14] Cost risk is not included in the calculation of life-cycle costs, because correlations among errors in estimates of non-recurring and recurring costs of different options must be known to calculate the cost risk of savings; it cannot be calculated simply by subtracting the cost risk of each option from the cost risk of the Interim Option with Titan IV.

Table 7-8. – Trade-offs: Investment versus Savings

Mission Model	Option	Nonrecurring Cost [a]	Savings or (Loss)[a,b]
Low-Growth	Enhanced Baseline	$1.2B	$3.5B
	Interim option with		
	Titan IV	$0.39B	$0B
	Titan V	$1.7B	$2.2B
	Shuttle-C	$1.3B	($4.8B)
	Transition Vehicle	$8.0B	$6.2B
	Advanced option with		
	Advanced Launch System	$14B	($2.1B)
	Shuttle II	$17B	($2.7B)
Growth	Interim option with		
	Titan IV	$2.0B	$0B
	Titan V	$3.0B	$2.0B
	Shuttle-C	$2.6B	($9.3B)
	Transition Vehicle	$9.3B	$13B
	Advanced option with		
	Advanced Launch System	$15B	$4.7B
	Shuttle II	$18B	($2.7B)
Expanded	Interim option with		
	Titan IV	$6.4B	$0B
	Titan V	$6.5B	$0.91B
	Shuttle-C	$6.1B	($25B)
	Transition Vehicle	$13B	$38B
	Advanced option with		
	Advanced Launch System	$18B	$28B
	Shuttle II	$23B	($2.7B)

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[a] In Fiscal Year 1988 dollars

b Relative to the Interim Option with Titan IV.

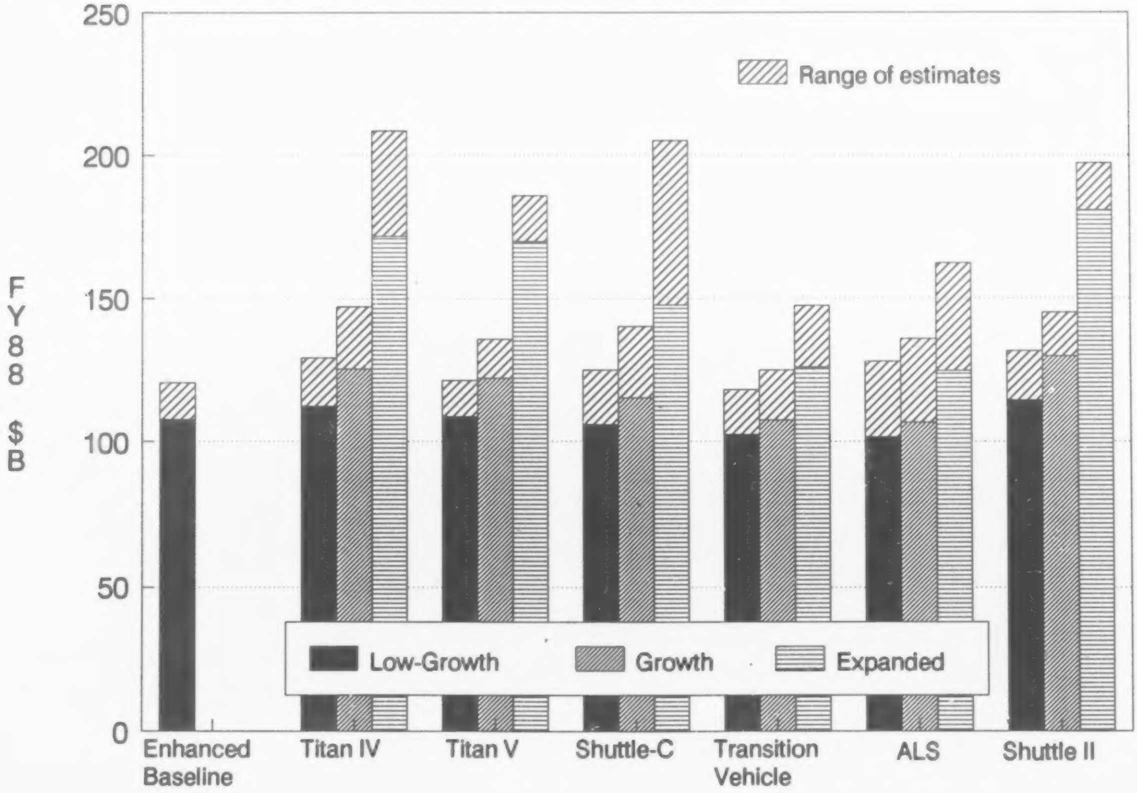
SOURCE: OTA and Boeing Aerospace Co.

ALTERNATIVE COST ESTIMATES

As noted earlier, the cost estimates quoted above are based in part on cost-estimating relationships (CERs) developed by Boeing Aerospace Company in the course of its work on the Space Transportation Architecture Study and the Advanced Launch System program, modified by OTA's and Boeing's estimates of reliability, failure cost, and cost risk. Two reviewers suggested alternative CERs, which in some cases, differ significantly from those provided by Boeing. Using these alternative CERs, OTA produced two alternative estimates of life-cycle cost.

Figure 7-12 shows the range spanned by the nominal and alternative estimates of option life-cycle costs (including failure costs and cost risk). Estimates for the Interim Option with Shuttle-C at Expanded launch rates lead to the greatest cost discrepancy. Estimates for the Interim Option with Titan IV also span a large range at Expanded launch rates. The differences between estimates for most options are comparable to the cost risk of the option as estimated by OTA and Boeing (see figure 7-11).

Figure 7-12. – Ranges of Estimated Costs



Appendix A

Cost Estimation Methodology

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Appendix A

Cost Estimation Methodology

SOURCES OF COST ESTIMATES

The nominal cost estimates quoted in chapter 7 were derived by OTA using data, estimates, and estimation methods developed by the Boeing Aerospace Company for the Space Transportation Architecture Study (STAS) and the Advanced Launch System program. OTA adjusted Boeing's estimates of failure costs for consistency with estimates of operations costs; OTA also estimated parameters not estimated by Boeing: cost risk (defined below) and reliabilities of 1) unmodeled systems (e.g. humans, weather) during ascent and payload deployment and 2) recovery of reusable vehicle systems.

The cost-estimating formulae developed by Boeing and used by OTA were reviewed by NASA, the Air Force, and the major launch vehicle producers. Several reviewers suggested important additions or corrections, and two suggested alternative formulae for estimating the costs of developing, producing, and launching some of the launch vehicles considered. Tables A-5 and A-7 summarize the formulas and the alternative suggestions. Using the alternative cost-estimating formulae proposed by the reviewers, OTA produced two alternative estimates of the life-cycle cost of each option in each mission model. These are tabulated in tables A-6 and A-8, along with estimates of failure cost and cost risk estimated by OTA. The ranges spanned by the OTA estimates and these alternative estimates are shown in figure 7-12.

COMPONENTS OF COST ESTIMATES

The major categories of costs are non-recurring and recurring costs. Non-recurring costs (investment) include costs of system design, development, testing, and evaluation (DDT&E), launch facility construction, and production of reusable flight hardware (e.g., Shuttle orbiters). Recurring costs include costs of planned operations and the expected costs of failures (including unplanned reflights). Table A-1 shows the cost-estimating relationships (CERs) used to estimate the costs of development, facilities, fleet procurement, and operations for each option.

DDT&E, Facility, & Fleet Production Costs

Incremental costs of new facilities are estimated as $150M per unit increase in annual launch rate capability above the current annual launch rate capability. This is roughly the cost of a new pad divided by the annual launch rate capability of a new pad. Actual costs of facilities must be incurred in larger increments – per pad, not per unit increase in annual launch rate capability.

Because they could use converted rather than new pads, Shuttle II and Titan V are assumed to have lower incremental costs of facilities for the first several units of annual launch rate capability: about $63M and $42M, respectively, per unit increase in annual launch rate capability to 16 per year for Shuttle II and 12 per year for Titan V. More precisely, it is assumed that for $1B all Shuttle pads could be modified to launch Shuttle II vehicles at a maximum annual launch rate of 16 per year. Similarly, it is assumed that for $500M all Titan IV pads could be modified to launch Titan Vs at a maximum annual launch rate of 12 per year. Additional Shuttle II or Titan V pads are assumed to cost $150M per unit increase in annual launch rate capability.

Non-recurring expenditures for DDT&E or facilities were assumed to be spread over a six-year period with 4 percent of the undiscounted cost incurred in the first year, 13 percent in the second year, 23 percent in the third year, 28 percent in the fourth year, 22 percent in the fifth year, and 10 percent in the sixth year. Spending on DDT&E for a vehicle ends the year before the assumed date of its initial launch capability (ILC). Spending on facility construction ends the year before an increased launch rate capability is required to fly all flights in the mission model.

In many types of serial production, the cost of producing an additional unit (the incremental unit cost) is lower than the cost of producing the previous unit. This effect is called the **learning effect**. The estimates of reusable element production costs in Table A-1 assume no learning.

Table A-1.—Nominal Cost-Estimating Relationships

Costs in Fiscal Year 1988 Dollars

Fleet	Dev.	Fac.	Limit	Prod.	Operations[a] per year	Operations[a] per launch
Shuttle	0	X	16/yr	0	$1,336M	$53M
Improved Shuttle	$0.6B	X	16/yr	0	$1,336M	$43M
Shuttle II	$12B	$1B + X	16/yr	3 x $1,500M	$59M	$33M
Shuttle-C	$1.2B	X	16 - STS	0	0	$236M - C
MLV	0	N/A	12+/yr	0	0	$35M
Titan IV	0	X	12/yr	0	$200M	$100M
Improved Titan IV	$0.4B	X	12/yr	0	$200M	$95M
Titan V	$1.2B	$0.5B + X	12/yr	0	$267M	$157M
Transition Vehicle	$3.9B	X	0	3 x $110M	$228M	$54M
ALS	$9.5B	X	0	4 x $425M	$241M	$33M

Dev.: development cost.

Fac.: launch facility conversion or construction cost.

Limit: maximum annual launch rate attainable without new facilities.

Prod.: cost of producing reusable elements.

X: $0.15B per unit increase in annual launch rate limit.

C: SSME credit: $80M if both SSMEs have flown on Shuttles until fully depreciated; pro-rated otherwise. A new SSME is assumed to cost $40M; its allowed lifetime on the Shuttle is assumed to be 10 flights until 1989, 20 flights from 1989 to1995, and 40 flights thereafter.

[a] Includes cost of producing expendable elements.

Operations costs

Operations costs include costs of producing expendable flight hardware (e.g., Titan IVs) and costs of planned launch, mission control, and recovery operations. The annual operations cost of an option is the sum of the annual operations costs of each fleet (type of launch vehicle) in the option. Annual fleet operations costs are assumed to have a fixed component, which must be paid each year regardless of the fleet launch rate, and a variable component equal to the fleet launch rate times an incremental cost per launch.

Operations costs were estimated using the cost-estimating relationships in Table A-1, which approximate more detailed relationships derived by Boeing Aerospace Company using its proprietary Ground Operations Cost Model. The Boeing model was based on operations cost data supplied by NASA and the Air Force and expendable hardware cost estimates obtained from Boeing's proprietary Internal Parametric Cost Model.[1]

The cost-estimating relationships in Table A-1 approximate the annual operations cost of each fleet as the sum of a fixed annual cost and a variable cost which, except for Shuttle-C, is proportional to the number of launches during the year. The incremental cost per launch (sometimes, imprecisely, called the "marginal" cost per launch) is therefore constant, except for Shuttle-C. The MLV and Shuttle-C fleets were assumed to have no fixed annual cost.

The incremental cost per launch includes the cost of producing expendable hardware. Because the incremental operations cost estimates in Table A-1 are constant (except for Shuttle-C), they reflect no **rate effect.**[2] Nevertheless, they reflect a decline in average unit cost as the production rate (mirroring the launch rate) is increased, because capital assets are more fully utilized and their cost can be amortized over a larger number of units.

---

[1] The Boeing Internal Parametric Cost Model is a set of cost-estimating relationships based on costs of Boeing products such as Saturn launch vehicles and the Inertial Upper Stage.

[2] In many types of serial production, the incremental unit cost declines when the production rate is increased; this effect is called a rate effect.

Shuttle-C operations cost is a special case, because Shuttle-C vehicles are assumed to use fully depreciated (i.e. free) Space Shuttle Main Engines (SSMEs) whenever they are available. An SSME becomes available after it has been used on the Shuttle for a "lifetime" – the maximum number of flights NASA deems safe for piloted missions. This lifetime has varied, and may continue to vary, in response to operational experience. Designed to have a 55-flight lifetime,[3] SSMEs have been qualified for only 20 flights, and NASA has indicated its intention to retire them after only 10 flights.[4,5] Boeing assumed a SSME lifetime of 10 flights (pre-1989), 20 flights (1989-1995), and 40 flights (post-1995). Based on this assumption, Boeing estimated that the equivalent of four fully depreciated SSMEs would be available at the beginning of the OTA mission models (in 1989), and that eight additional fully depreciated SSMEs would be available by 1995, the assumed year of initial launch capability (ILC) for Shuttle-C.

Boeing assumed that when SSMEs are not available, new SSMEs will be purchased for Shuttle-C at an estimated cost of $40M each. Without the SSME credit (which would be only $2M per flight in the out-years of the Low-Growth mission model, or $0.5M in the out-years of the Expanded mission model), the incremental operations cost of Shuttle-C would be $236M per launch – over four times the assumed incremental operations cost of the current Shuttle, over twice the assumed incremental operations cost of Titan IV, and over seven times the assumed incremental operations cost of the Advanced Launch System. Non-engine-related incremental costs of Shuttle-C include $55M for the payload module (including payload cradles), $55M for the boattail, and $56M for other parts. No costs of using, recovering, and refurbishing Orbital Maneuver Vehicles (OMVs) for docking Shuttle-C to the space station are included.

Costs of Failures

Operations costs estimated by OTA include expected costs of failure. These are not included in the operations CERs of Table A-1, but must be calculated separately using estimates of vehicle reliabilities and expected cost per failure of each type of vehicle. Costs of failure include costs of replacing the launch vehicle and payload, attempting to determine and correct the cause of failure, and the costs of downtime (e.g., salaries and wages for launch vehicle and payload operation and maintenance personnel).

The expected failure cost **per flight** for each type of vehicle is the product of the probability of failure (in a single launch attempt) and the expected cost **per failure** for that type of vehicle. Multiplying this product by the number of flights to be attempted with that type of vehicle in a particular year yields the expected annual failure cost for that fleet in that year. Adding the expected annual failure costs of all other fleets in an option yields the annual failure cost expected for the option, which is a component of the funding profiles exhibited in chapter 7. It is also multiplied by a discount factor to obtain the discounted annual failure cost for the option. The discounted failure costs for each year in the mission model are then added to obtain the present value of failure costs for the option, which is shown in figures 7-8 – 7-11.

Reliability estimation: The most difficult and least credible part of this procedure is estimating the probability of failure for each vehicle. This is particularly true for proposed vehicles that have not been fully designed, much less built, tested, and flown. The only completely objective method of estimating a vehicle's probability of failure is by statistical analysis of the number of failures observed in actual launches of identical vehicles under conditions representative of those under which future launches will be attempted. Such an analysis cannot ascertain the reliability with perfect accuracy and confidence, but it can determine, for example, that the reliability is within a certain range of possible values (called a confidence interval) with a corresponding statistical confidence.[6] As more launches are observed, the confidence interval corresponding to a given confidence level becomes narrower (i.e., the reliability is known with greater accuracy), and the confidence level corresponding to a given confidence interval becomes greater (i.e., the reliability is known with greater confidence). However, a large number of launches must be observed to confirm that reliability is high with high confidence.

For example, if one failure were observed in 1000 attempted launches, one could conclude that the reliability was 99.3 percent with 99.3 percent confidence. One would **not** be justified in concluding that the reliability was the observed success rate (99.9 percent). If one required confirmation of 99.9 percent reliability (or better) with 99.9 percent confidence (or better), there must be no failures in 6905 attempted launches; but there would be a 99.9 percent chance of at least one failure in any series of 6905 launch attempts if the vehicles **were** 99.9 percent reliable. Hence it would be virtually impossible to **demonstrate** 99.9 percent reliability in a flight test program.

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[3] NRC, Assessment of Constraints on Space Shuttle Launch Rates (Washington, DC: National Academy Press, April 1983), p. 22.

[4] Dale D. Myers, Deputy Administrator, NASA, letter to Robert K. Dawson, Associate Director for Natural Resources, Energy and Science, EOP, OMB, January 26, 1988.

[5] As lifetime decreases, Shuttle costs rise and Shuttle-C costs fall.

[6] Y. Fujino, Biometrika, vol. 67, no. 3, 1980, pp. 677-681; C.R. Blyth & H.A. Still, Journal of the American Statistical Association, vol. 78, no. 381, March 1983, pp. 108-116.

Hence although this method may provide useful, **objective** information about the reliability of vehicles with long operational histories, using it to confirm the estimated reliabilities of new vehicles before they become operational would require a prohibitively long flight test program. And of course strict statistical estimation cannot be used at all to estimate the reliabilities of vehicles not yet built.

The **design reliability** of proposed vehicles is generally estimated using:

- data from laboratory tests of vehicle systems (e.g., engines and avionics) and components that have already been built;
- engineers' judgements about the reliability achievable in systems and components that have not been built;
- analyses of whether a failure in one system or component would cause other systems and components, or the vehicle, to fail; and
- assumptions (often tacit) that:
  - the laboratory conditions under which systems were tested precisely duplicate the conditions under which the systems will operate,
  - the conditions under which the systems will operate are those under which they were designed to operate,
  - the engineers' judgements about reliability are correct, and
  - the failure analyses considered all circumstances and details that influence reliability.

Such "engineering estimates" of design reliability are incomplete and subjective. However, the subjectivity and uncertainty often are not exhibited. There are methods for assessing and exhibiting the uncertainties of experts called upon to estimate reliabilities of components,[7] and probabilistic risk assessment (PRA) methods for estimating risks posed by unreliability, considering the uncertainties in the estimates of components' reliabilities.[8] However, it is more difficult and time-consuming to use them than to provide a single "best estimate" of reliability showing no uncertainty, so the latter has been standard engineering practice except for tasks – such as safety analysis of nuclear reactors – for which the increased rigor has been deemed worth the effort.[9]

In the wake of the Challenger accident, the National Research Council Committee on Shuttle Criticality Review and Hazard Analysis Audit has recommended that NASA use probabilistic risk assessment methods to assess Space Transportation System risks and hazards quantitatively, even if partially subjectively. Some PRA methods (e.g., Bayesian methods[10]) are well-suited for reliability estimation throughout a vehicle's life cycle, because they allow reliability of unbuilt components of proposed vehicles to be estimated subjectively – but quantitatively – at first, on the basis of engineering judgement, and they allow these estimates to be adjusted later, in a logically consistent manner, on the basis of laboratory tests of components and, later still, on the basis of vehicle flight experience. Probabilistic risk assessment methods also make subjectivity and uncertainties explicit and auditable.

Resource limitations precluded OTA from using such methods to estimate the reliability assumed in calculating the expected failure costs shown in chapters 1 and 7 and in this appendix. For these estimates, OTA used engineering estimates of vehicle design reliability for payload deployment; these are shown in Table A-2. These component reliabilities are estimated from test data and flight experience when relevant data were available.

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[7] For a recent review and critique, see T. Mullin, "Experts' estimation of uncertain quantities and its implications for knowledge acquisition," IEEE Transactions on Systems, Man, and Cybernetics [to be published Jan./Feb. 1989].

[8] See, for example, S. Kaplan and B.J. Garrick, "On the quantitative definition of risk," Risk Analysis, vol. 1, no. 1, 1981, pp. 11-27, and National Research Council Committee on Shuttle Criticality Review and Hazard Analysis Audit, Post-Challenger Assessment of Space Shuttle Risk Assessment and Management (Washington, DC: National Academy Press, January 1988), Appendix D.

[9] E.J. Lerner, "An Alternative to 'Launch on Hunch,'" Aerospace America, May 1987, p. 40.

[10] National Research Council Committee on Shuttle Criticality Review and Hazard Analysis Audit, op. cit., Appendix D, provides a tutorial overview. David A. Schum, in Evidence and Inference for the Intelligence Analyst (New York: University Press of America, 1987), provides a longer, epistemological critique of Bayesian inference. See also M.W. Merkhofer, "Comparative Evaluation of Quantitative Decision-Making Approaches," contractor report prepared for the National Science Foundation (Springfield, VA: National Technical Information Service, April 1983).

Table A-2. – Engineering Estimates of Reliabilities

	Solid Rockets			Liquid Rockets			Avionics			Vehicle
	No.	FT?	Rel.	No.	FT?	Rel.	No.	FT?	Rel.	
Shuttle	2	No	.994	3	No	.988	5	Yes	neg	.982
Impr. Shuttle	2	No	.998	3	No	.988	5	Yes	neg	.986
Shuttle II	0	--	--	9	Yes	.999	many	Yes	neg	.999
Shuttle-C	2	No	.994	2	No	.992	" ?	Yes	neg	.986
Titan IV	2	No	.997	3	No	.988	1	No	.988	.972
Impr. Titan IV	2	No	.992	3	No	.988	many	Yes	neg	.976
Titan V	2	No	.998	6	No	.976	many	Yes	neg	.974
Transition	0	--	--	9	Yes	.999	many	Yes	neg	.999
ALS	0	--	--	9	Yes	neg	many	Yes	neg	.999 +
MLV	9	No	.989	2	No	.994	some	some	.992	.975

Vehicle.: reliability of ascent and payload deployment.
No.: number of rockets or independent "strings" of electronic systems which perform the same function.
FT: fault-tolerant.
Rel.: net reliability, considering redundancy.
neg: negligible contribution to unreliability, assuming other vehicle systems are 99.95 percent reliable.
SOURCE: Boeing Aerospace Co.

The estimated **payload-deployment** reliability of each vehicle does not include the unreliability of down-cargo return or recovery of reusable vehicles or components. Moreover, it includes only unreliability due to design faults; it excludes unreliability due to induced faults (e.g., negligence or sabotage) or operations under conditions (e.g. temperature) outside of specified limits. Hence these engineering estimates must be regarded as partially subjective, displaying more certainty than can be justified on the basis of strictly objective statistical inference.[11]

To estimate the total failure probability, OTA multiplied Boeing's estimates of payload deployment reliability by 0.99 to reflect a 1 percent probability (assumed by OTA) of failure during ascent or payload deployment caused by phenomena not modeled in the engineering estimates – e.g., human error, negligence, or malice, or unexpected weather or lightning, etc. OTA also assumed a 1 percent probability of failure during recovery of reusable vehicle elements. Table A-3 shows the resulting reliability estimates used by OTA to estimate failure costs. OTA is **not** confident that 1 percent is the **correct** probability of failure during recovery, or of unmodeled failure during ascent; these assumed probabilities are actually optimistic compared to reliability inferred objectively from historical data. For example, a history of 24 successful Shuttle orbiter recoveries in 24 attempts indicates only that the reliability of Shuttle orbiter recovery has been between

Table A-3. – OTA Estimates of Reliabilities

Vehicle	Reliability
Shuttle	96.2 %
Improved Shuttle	96.6 %
Shuttle II	97.9 %
Shuttle-C	96.6 %
Titan IV	96.2 %
Improved Titan IV	96.6 %
Titan V	96.4 %
Transition	97.9 %
ALS (flyback)	97.9 %
(expendable)	97.9 %
MLV	96.5 %

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[11] Objective uncertainties in the reliabilities of tested vehicles are indicated by confidence intervals quoted in (e.g.) Boeing Aerospace Co., Launch Systems for the Strategic Defense Initiative -- Data Book, (Los Angeles, CA: Headquarters, Space Division, U.S. Air Force Systems Command, 1986), pp. 6-84 - 6-85, and U.S. Congress, Office of Technology Assessment, Reducing Launch Operations Costs: New Technologies and Practices, OTA-TM-ISC-28 (Washington, DC: U.S. Government Printing Office, in press 1988), appendix B.

90.6 percent and 100 percent with 90.6 percent confidence.

Cost per failure: Estimating the average cost per failure is also difficult. For one thing, there will generally be intangible costs (e.g. risk to national security) as well as cash outlays (e.g., to replace a payload or launch vehicle). Assessment of intangible costs such as risk to national security is difficult and would be controversial, because it would require quantitative value judgements.[12] Intangible costs could be largely averted by purchasing spare vehicles **and payloads** and flying missions "at risk" after failures. Otherwise, costs of delays after failure would include intangible costs and would depend on decisions on grounding fleets of vehicles with common critical components and on returning fleets to operational status. Such decisions are not now made on the basis of probabilistic risk assessment.

The cost of the Challenger failure has been estimated at over $13.5 billion by Boeing. About half of this cost was attributed to delays in Shuttle operations and payload processing. The second largest contribution ($3.7 billion) was for miscellany—added costs of debt service, insurance, special order production, etc. The third largest contribution ($1.5 billion) was for replacement of the launch vehicle, and a nearly equal amount ($1.4 billion) was spent for accident investigation, corrective action, and reflight. The smallest contribution ($260 million) was for replacement of the cargo.

Based on this estimated cost per failure, Boeing recommended assuming that a manned mission failure (Shuttle or Shuttle II) would cost $10 billion on the average. This would be a reasonable assumption if the effect of downtime on option life-cycle cost were modeled in a consistent manner. However, Boeing estimated life-cycle costs for OTA's options by assuming uninterrupted operations, so for consistency OTA assumes a Shuttle failure cost of $7 billion, i.e., the costs of delay due to downtime are excluded [as they were in the Space Transportation Architecture Study]. Consistency also requires that vehicle replacement cost be interpreted as the cost of procuring a spare vehicle in advance so that Shuttle launch rates will not be reduced after a failure.[13] These assumptions are likely to be violated; most likely, no spare orbiter will be procured, and if another failure occurs, the Shuttle fleet will stand down, and some lost payloads may not be replaced and reflown. However, it would be more difficult to pose and analyze the implications of consistent alternative assumptions about the length and costs of downtime and the effect of corrective action on reliability; such an effort was not attempted in the Space Transportation Architecture Study and has not been attempted by Boeing or OTA.

Boeing also recommended assuming an average failure cost of $2 billion for heavy cargo vehicles and $300 million for MLVs. For consistency, OTA reduced the estimated failure cost of heavy cargo vehicles except Shuttle-C by $100 million—the estimated operations cost for the Titan IV fleet at a launch rate of zero for six months, the average Titan 34D downtime observed to date. Boeing's operations cost model (table A-1) assumes that Shuttle-C and MLV fleets have no fixed operations costs (i.e. while not launching), so OTA did not reduce the costs estimated by Boeing for Shuttle-C and MLV failures.

Finally, OTA assumed the average cost per failure of a partially reusable heavy cargo vehicle (a Transition launch vehicle or an Advanced Launch System launch vehicle) during recovery is about $1.5 billion. This represents the approximate cost of replacing one of two recoverable elements (propulsion/avionics module or flyback booster) and expenses of accident investigation and corrective action, etc.

To summarize, OTA assumed average costs per failure of $7 billion for the Shuttle or Shuttle II on ascent or return, $2 billion for Shuttle-C, $1.9 billion for other heavy cargo vehicles ($1.5 billion for a recovery failure, if partially reusable), and $300 million for MLVs.

Assuming further that failure costs are incurred in the year of failure, OTA also calculated the present value of the expected failure cost of each option, discounted at 5 percent. These are included in the histograms comparing life-cycle costs in chapters 1 and 7. OTA also calculated the 70th percentile of the discounted failure cost of each option; the 70th percentile minus the expected discounted failure cost is used as the component of cost risk (see below) due to more failures than expected.

Cost Risk

Cost risk was defined in the Space Transportation Architecture Study as the cost overrun, expressed as a percentage of the estimated present value of life-cycle cost (discounted 5 percent per year), that is expected with a subjectively estimated probability of 30 percent,

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[12] U.S. Congress, Office of Technology Assessment, Anti-Satellite Weapons, Countermeasures, and Arms Control, OTA-ISC-281 (Washington, DC: U.S. Government Printing Office, 1985), p. 33.

[13] It is implausible to assume that every payload flown would be, or should be, backed up by a spare. Including payload replacement and reflight cost in the failure cost could represent either the cost of a spare or, if there is no spare, the utility cost of a failure.

Table A-4. – Cost Risk[a]

Option	Non-Recurring Cost Risk	Recurring Cost Risk
Enhanced	0%	13%
Titan IV	0%	14%
Titan V	2%	13%
Shuttle-C	4%	17%
Transition LV	14%	17%
ALS		
– with fly-back booster	14%	17%
– with expendable LV	2%	13%
Shuttle II	29%	18%

[a] "STAS component" – excludes risk of greater-than-expected failure costs.

assuming the Space Transportation Architecture Study groundrules are met. Higher overrruns are judged less probable. Cost risk was intended to represent likely increases in life-cycle cost caused by unforeseen difficulties in technology development, facility construction, etc. However, it did not include risks of cost growth due to mission cancellations, funding stretch-outs, or standdowns after failure, which were excluded by the Space Transportation Architecture Study groundrules.

The cost risk quoted by OTA in chapters 1 and 7 includes cost risk as defined in the Space Transportation Architecture Study as well as a risk of greater-than-expected failure costs. It excludes risks of cost growth due to mission cancellations, funding stretch-outs, or standdowns after failures.

The "STAS component" of cost risk includes the risk of growth in costs of DDT&E, facilities, and production (adjusted for changes in inflation and production rate). OTA assumes that the STAS component of each option's cost risk has non-recurring and recurring components as estimated by Boeing Aerospace Company[14] for corresponding STAS options (see Table A-4) featuring similar or identical launch vehicles, as well as backup launch vehicles and upper stages not considered here. This analysis also assumes that the errors in the estimates of non-recurring and recurring costs of an option are normally distributed and uncorrelated.[15]

Failure cost risk represents expected fluctuations in failures per year, assuming vehicle reliabilities are known.[16] The total failure cost risk for an option is the sum of the failure cost risks for each fleet. OTA defines the failure cost risk for each fleet as the difference between its expected failure cost and the 70th percentile of failure cost.

Mission cancellations, funding stretch-outs, or standdowns after failures could have diverse, complicated, poorly-understood, and policy-dependent effects on life-cycle cost. They could **decrease** life-cycle cost while increasing average life-cycle cost per launch and causing intangible costs of delaying mission capabilities to be incurred. These intangible costs should be considered a cost of the space transportation system only if they are caused by the space transportation system (e.g. by a standdown).

Mission cancellations could be caused by the space transportation system (e.g. greater-than-expected vehicle processing time), payload production delays, lack of need (e.g. greater-than-expected longevity of satellites scheduled for replacement), or funding stretch-outs.

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[14] Boeing Aerospace Company, Space Transportation Architecture Study – In-Progress Review Number 5, Apr. 7, 1987.

[15] Boeing assumed that total cost risk was the sum of non-recurring cost risk and recurring cost risk, which implies a tacit assumption that the errors in the estimates of non-recurring and recurring costs are perfectly correlated. It is equally plausible that a reduction in non-recurring cost (e.g. for budgetary reasons) could increase recurring cost. We split the difference by assuming they are uncorrelated.

[16] In fact, uncertainties in vehicle reliabilities (described above) would also contribute.

Funding could be stretched out by the Administration or Congress in response to mission cancellations or changing national priorities. Logically consistent estimation of total cost risk must account for these possibilities and will require more sophisticated methods than were used here, or in the Space Transportation Architecture Study.

Cancellation of planned missions may cause stretch-outs in production, or vice versa. Stretch-outs in production have been a major contributor to cost growth of weapon systems,[17] and are probably the leading contributor in the 1980s.[18]

Only about 70 percent of DoD missions projected one to five years in advance by the Air Force have actually been launched.[19] Even fewer missions projected by NASA have been launched. The baseline mission model assumed in a 1971 economic analysis of the (then) proposed Space Shuttle postulated 736 flights during 1978-1990; the next year, the baseline was reduced to 514 flights during 1979-1990.[20] This will prove to be a tenfold overestimate if 20 more Shuttle flights are flown before 1991 as now planned.[21] In 1979, NASA projected total U.S. launch activity[22] in 1985 would be 44 equivalent Shuttle flights.[23] This estimate was revised downward as 1985 approached; about 12 equivalent Shuttle flights were actually flown.[24]

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[17] H.Rep. 96-656, op. cit., and U.S. Congress, Congressional Budget Office, Effects of Weapons Procurement Stretch-Outs on Costs and Schedules (Washington, DC: U.S. Congress, Congressional Budget Office, November 1987).

[18] M. Rich and E. Dews, Improving the Military Acquisition Process R-3373 (Santa Monica, CA: The Rand Corporation, Feb. 1986).

[19] DoD/NASA Space Transportation Joint Task Team, National Space Transportation and Support Study 1995-2010, Annex A (Washington, DC: NASA Headquarters, Code M, May 1986), pp. 14-18.

[20] K.P. Heiss and O. Morgenstern, Economic Analysis of the Space Shuttle System, Executive Summary, (Washington, DC: NASA, 1972).

[21] NASA, Payload Flight Assignments – NASA Mixed Fleet, March 1988.

[22] For DoD, NASA, other government agencies, and domestic and foreign commercial customers.

[23] U.S. Congress, Congressional Budget Office, Setting Space Transportation Policy for the 1990s (Washington, DC: Congressional Budget Office, October 1986).

[24] Ibid.

Alternative Cost Estimates

Alternative Assumptions by Reviewer One and Results

Table A-5 summarizes the cost-estimating formulas developed by Boeing as modified in accordance with the recommendations of one reviewer. This reviewer had not estimated the costs of the Improved Titan IV, Titan V, and Transition launch vehicles, and suggested no change in OTA's cost-estimating formulae for these proposed vehicles.

OTA produced alternative estimates of the life-cycle cost of each option in each mission model using the alternative cost-estimating formulae proposed by this reviewer, Boeing's cost-estimating formulae for the Improved Titan IV, Titan V, and Transition launch vehicles, and OTA's estimates of failure cost and cost risk. These option life-cycle cost estimates are tabulated in Table A-6.

Table A-5. – Alternate Cost-Estimating Relationships #1

Costs in Fiscal Year 1988 Dollars

					---- Operations[a] ----	
Fleet	Dev.	Fac.	Limit	Prod.	per year	per launch
Shuttle	0	X	14/yr	0	$2,162M	$43M
Improved Shuttle	$0.6B	X	14/yr	0	$2,162M	$43M
Shuttle II	$12B	$1B + X	14/yr	3 x $1,500M	$99M	$48M
Shuttle-C	$0.75B	$0.02-0.05B + X	14 - STS	0	0	$163M - C
MLV	0	X	12 + /yr	0	$35M	$33M
Titan IV	0	X	12/yr	0	$162M	$146M
Improved Titan IV	$0.4B	$0.5B + X	12/yr	0	$200M	$95M
Titan V	$1.2B	$0.5B + X	12/yr	0	$267M	$157M
Transition Vehicle	$3.9B	X	0	3 x $110M	$228M	$54M
ALS	$9.5B	X	0	4 x $425M	$230M	$75M

Dev.: development cost.

Fac.: launch facility conversion or construction cost.

Limit: maximum annual launch rate attainable without new facilities.

Prod.: cost of producing reusable elements.

X: $0.15B per unit increase in annual launch rate limit (OTA's nominal estimate). This reviewer did not estimate the cost of increasing the annual launch rate limit by large increments.

C: SSME credit: $80M if both SSMEs have flown on Shuttles until fully depreciated (10 flights); pro-rated otherwise. This reviewer expressed the annual cost as $412M per year plus $119M per flight at 3 Shuttle-C flights per year and 11 Shuttle flights per year.

[a] Includes cost of producing expendable elements.

Table A-6.—Alternative Cost Estimate #1

in Fiscal Year 1988 Dollars

	Life-cycle cost			Cost risk		
Option	Nonrec.	Operations	Failures	Nonrec.	Recur.	Total[a]
	Low-Growth					
Enhanced Baseline	$1.2B	$54B	$40B	0	$25B	$120B
Titan IV	$0.4B	$60B	$42B	0	$27B	$129B
Titan V	$1.7B	$57B	$38B	$0.03B	$25B	$121B
Shuttle-C	$0.9B	$60B	$37B	$0.04B	$27B	$125B
Transition Vehicle	$8.0B	$49B	$35B	$1.1B	$26B	$118B
Advanced Launch SysteB	$13.9B	$51B	$37B	$1.9B	$27B	$128B
Shuttle II	$16.7B	$49B	$27B	$4.8B	$22B	$114B
	Growth					
Titan IV	$2.0B	$69B	$47B	0	$28B	$147B
Titan V	$3.0B	$65B	$41B	$0.06B	$26B	$136B
Shuttle-C	$2.2B	$68B	$41B	$0.09B	$29B	$140B
Transition Vehicle	$9.3B	$52B	$37B	$1.3B	$26B	$125B
Advanced Launch System	$15B	$54B	$39B	$2.1B	$27B	$136B
Shuttle II	$18.3B	$58B	$32B	$5.3B	$24B	$133B
	Expanded					
Titan IV	$6.4B	$104B	$65B	0	$34B	$209B
Titan V	$6.5B	$95B	$54B	$0.1B	$30B	$186B
Shuttle-C	$5.8B	$99B	$54B	$0.2B	$35B	$194B
Transition Vehicle	$12.7B	$63B	$44B	$1.8B	$29B	$148B
Advanced Launch System	$17.8B	$66B	$48B	$2.5B	$30B	$162B
Shuttle II	$22.7B	$93B	$49B	6.6B	$32B	$197B

Nonrec.: nonrecurring.

Rec.: recurring.

[a] Total cost includes total cost risk, which is the square root of the sum of the squared components of cost risk (nonrecurring and recurring).

SOURCE: OTA.

Alternative Assumptions by Reviewer Two and Results

Table A-7 summarizes the cost-estimating formulas developed by Boeing as modified in accordance with the recommendations of a different reviewer. This reviewer suggested changes only in the cost-estimating formulae for the Shuttle-C, Shuttle II, and Advanced Launch System vehicles, and in facility costs for expendable vehicles. The reviewer also proposed a cost-estimating formula for an expendable Advanced Launch System launch vehicle.

OTA produced alternative estimates of the life-cycle cost of each option in each mission model using the alternative cost-estimating formulae proposed by this reviewer for Shuttle-C, Shuttle II, and Advanced Launch System vehicles, and facilities, Boeing's cost-estimating formulae for the other launch vehicles, and OTA's estimates of failure cost and cost risk. These option life-cycle cost estimates are tabulated in Table A-8. For these estimates, OTA assumed that the Advanced Launch System launch vehicle would be expendable and would have a potential reliability of 98.9 percent and an actual reliability of 97.9 percent.

Table A-7.—Alternative Cost-Estimating Relationships #2

Costs in Fiscal Year 1988 Dollars

					----Operations[a]----	
Fleet	Dev.	Fac.	Limit	Prod.	per year	per launch
Shuttle	0	X	16/yr	0	$1,336M	$53M
Improved Shuttle	$0.6B	X	16/yr	0	$1,336M	$43M
Shuttle II	$24B	$1B + X	16/yr	3 x $3,000M	$59M	$33M
Shuttle-C	$1.2B	X	16 - STS	0	$480M[b]	$80M[b]
MLV	0	0	12 + /yr	0	0	$35M
Titan IV	0	X	12/yr	0	$200M	$100M
Improved Titan IV	$0.4B	X	12/yr	0	$200M	$95M
Titan V	$1.2B	$0.5B + X	12/yr	0	$267M	$157M
Transition Vehicle	$3.9B	X	0	3 x $110M	$228M	$54M
ALS (flyback)	$12.3B	X	0	4 x $425M	$630M[c]	$31M[c]
ALS (ELV)	$2.8B	X	0	4 x $425M	$240M[d]	$40M[d]

Dev.: development cost.

Fac.: launch facility conversion or construction cost.

Limit: maximum annual launch rate attainable without new facilities.

Prod.: cost of producing reusable elements.

X: $0.15B per unit increase in annual launch rate limit.

C: SSME credit: $80M if both SSMEs have flown on Shuttles until fully depreciated; pro-rated otherwise. A new SSME is assumed to cost $40M; its allowed lifetime on the Shuttle is assumed to be 10 flights until 1989, 20 flights from 1989 to1995, and 40 flights thereafter.

[a] Includes cost of producing expendable elements.

[b] Expressed by this reviewer as an average cost of $140M per launch at 8 per year and $104M per launch at 20 per year; expressed in this form by OTA.

[c] Expressed by this reviewer as an average cost of $110.25M per launch at 8 per year and $63M per launch at 20 per year; expressed in this form by OTA.

[d] Expressed by this reviewer as an average cost of $70M per launch at 8 per year and $52M per launch at 20 per year; expressed in this form by OTA.

Table A-8.—Alternative Cost Estimate #2

in Fiscal Year 1988 Dollars

	Life-cycle cost			Cost risk		
Option	Nonrec.	Operations	Failures	Nonrec.	Recur.	Total[a]
	Low-Growth					
Enhanced Baseline	$0.9B	$42B	$40B	00	$25B	$108B
Titan IV	$0.1B	$44B	$43B	0	$26B	$112B
Titan V	$1.4B	$45B	$38B	$0.03B	$24B	$109B
Shuttle-C	$1.1B	$42B	$37B	$0.04B	$26B	$106B
Transition Vehicle	$6.2B	$38B	$35B	$0.1B	$24B	$102B
Advanced Launch System	$4.9B	$37B	$35B	$0.7B	$25B	$102B
Shuttle II	$32.0B	$36B	$36B	$9B	$25B	$132B
	Growth					
Titan IV	$0.5B	$50B	$47B	0	$27B	$126B
Titan V	$1.8B	$54B	$41B	$0.04B	$25B	$122B
Shuttle-C	$1.4B	$46B	$41B	$0.06B	$27B	$115B
Transition Vehicle	$6.2B	$41B	$37B	$0.1B	$24B	$108
Advanced Launch System	$5.3B	$39B	$37B	$0.7B	$25B	$107B
Shuttle II	$32.5B	$43B	$41B	$9.4B	$27B	$145B
	Expanded					
Titan IV	$1.7B	$74B	$65B	0	$31B	$172M
Titan V	$2.7B	$83B	$54B	$0.05B	$29B	$170B
Shuttle-C	$2.4B	$61B	$54B	$0.09B	$30B	$148B
Transition Vehicle	$6.2B	$46B	$45B	$0.1B	$25B	$126B
Advanced Launch System	$6.2B	$46B	$50B	$0.9B	$27B	$125B
Shuttle II	$33.7B	$70B	$58B	$9.8B	$32B	$192B

Nonrec.: nonrecurring.

Recur.: recurring.

[a] Total cost includes total cost risk, which is the square root of the sum of the squared components of cost risk (nonrecurring and recurring).

SOURCE: OTA.

Appendix B

Cost Estimates in Current Dollars

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Appendix B

Cost Estimates in Current Dollars

INVESTMENT AND SAVINGS IN "THEN-YEAR" DOLLARS

Table B-1 shows the investment required, in current ("then-year") dollars, for each option OTA considered, as well as its undiscounted savings in life-cycle cost compared to the estimated life-cycle cost of the Interim Option with Titan IV. A constant inflation rate of 4.2 percent per year—the projected gross national product inflation rate—was assumed. Historically, space system prices have inflated at rates between one and two times the GNP inflation rate.

Table B-1 may be compared with table 7-8 of ch. 7, which shows corresponding investment and savings, discounted 5 percent per year, in constant 1988 dollars.

Table B-1.—Investment and Savings in "Then-Year" Dollars

Mission Model	Option	Nonrecurring Cost	Savings or (Loss)*
Low-Growth	Enhanced Baseline	$2.1B	$16B
	Interim option with		
	Titan IV	$0.9B	$0B
	Titan V	$2.8B	$13B
	Shuttle-C	$2.1B	($18B)
	Transition Vehicle	$12B	$46B
	Advanced option with		
	Advanced Launch System	$31B	$25B
	Shuttle II	$37B	$29B
Growth	Interim option with		
	Titan IV	$3.5B	$0B
	Titan V	$4.9B	$11B
	Shuttle-C	$4.2B	($38B)
	Transition Vehicle	$14B	$77B
	Advanced option with		
	Advanced Launch System	$34B	$56B
	Shuttle II	$40B	$29B
Expanded	Interim option with		
	Titan IV	$10B	$0B
	Titan V	$10B	$3.8B
	Shuttle-C	$9.4B	($110B)
	Transition Vehicle	$20B	$180B
	Advanced option with		
	Advanced Launch System	$40B	$160B
	Shuttle II	$47B	$29B

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* Relative to Interim option with Titan IV.

SOURCE: OTA and Boeing Aerospace Co.

FUNDING PROFILES IN "THEN-YEAR" DOLLARS

Figure B-1.—Funding Profile for Enhanced Baseline Option

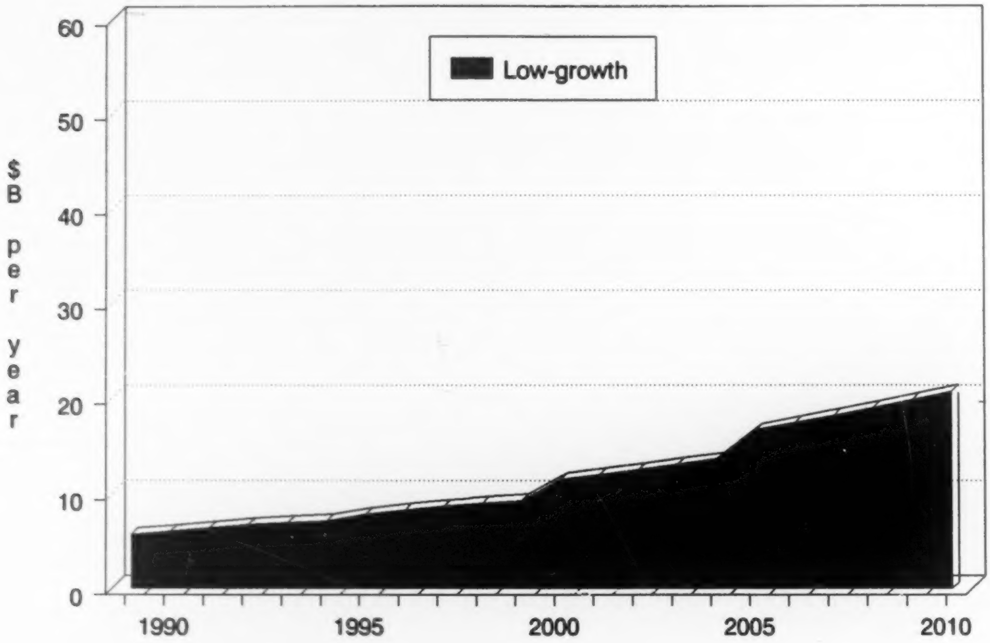


Figure B-2. – Funding Profiles for Interim Option with Titan IV

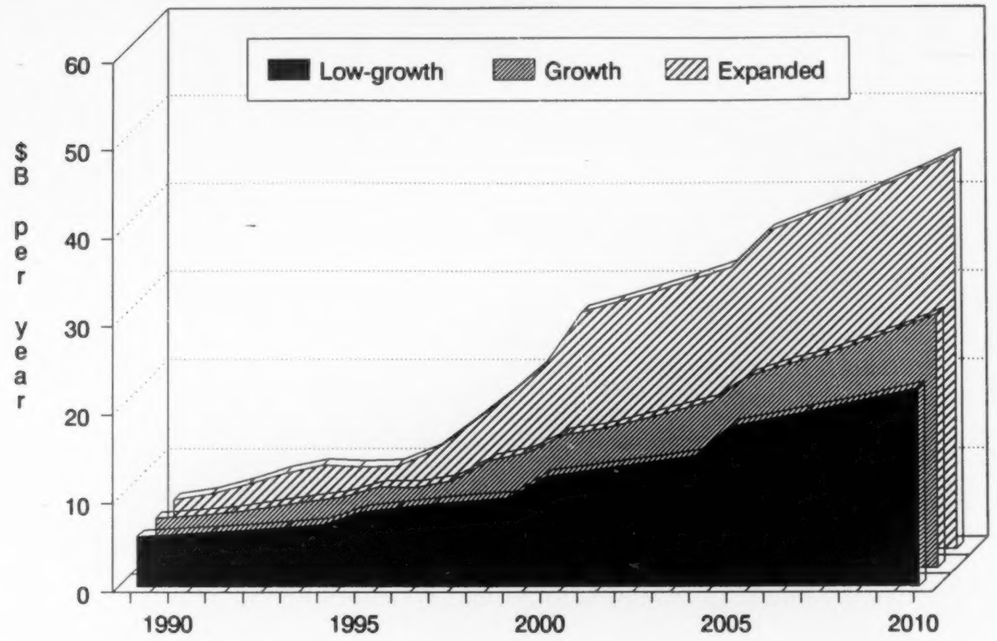


Figure B-3. – Funding Profiles for Interim Option with Titan V

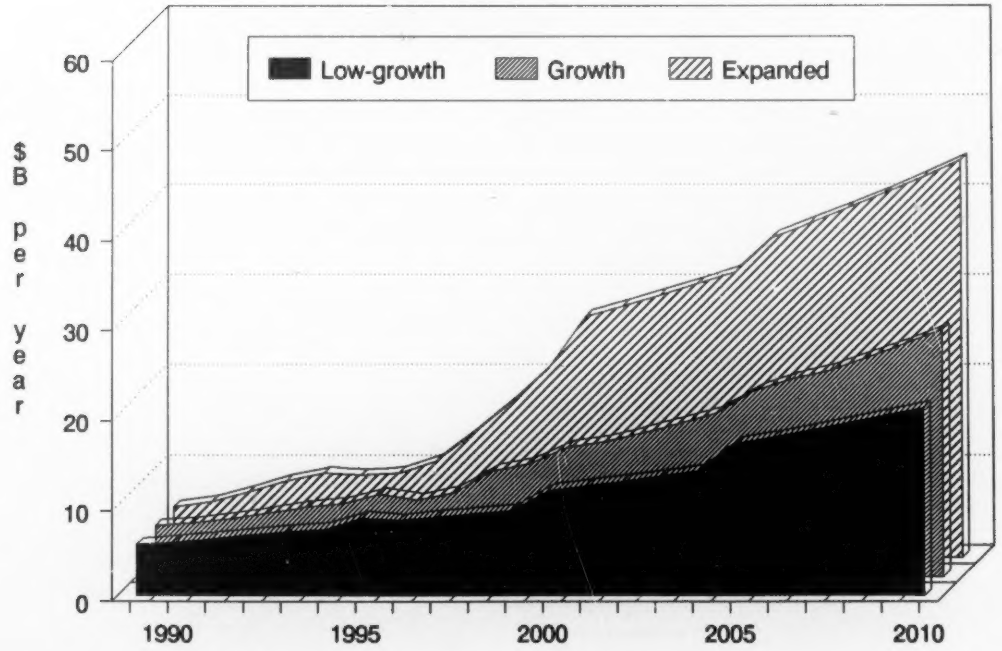


Figure B-4.—Funding Profiles for Interim Option with Shuttle-C

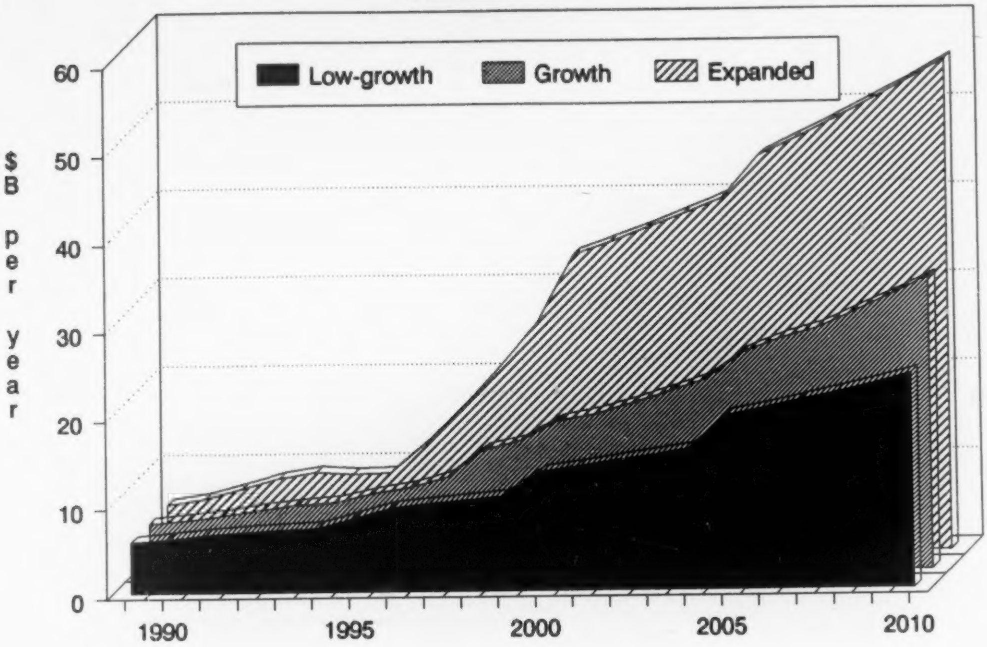


Figure B-5.—Funding Profiles for Interim Option with Transition Launch Vehicle

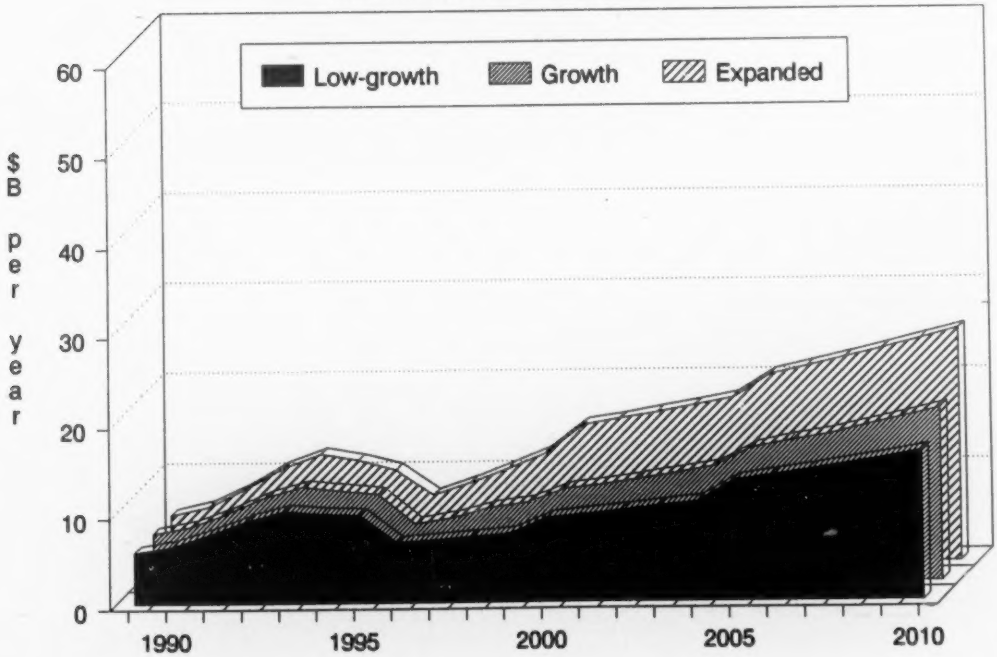


Figure B-6. – Funding Profiles for Advanced Option with Advanced Launch System

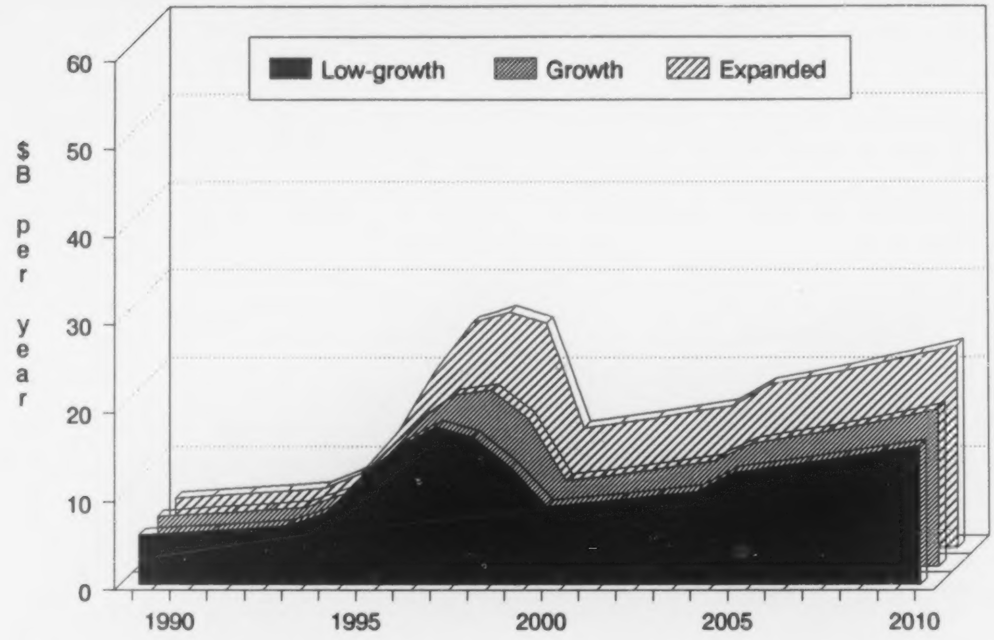
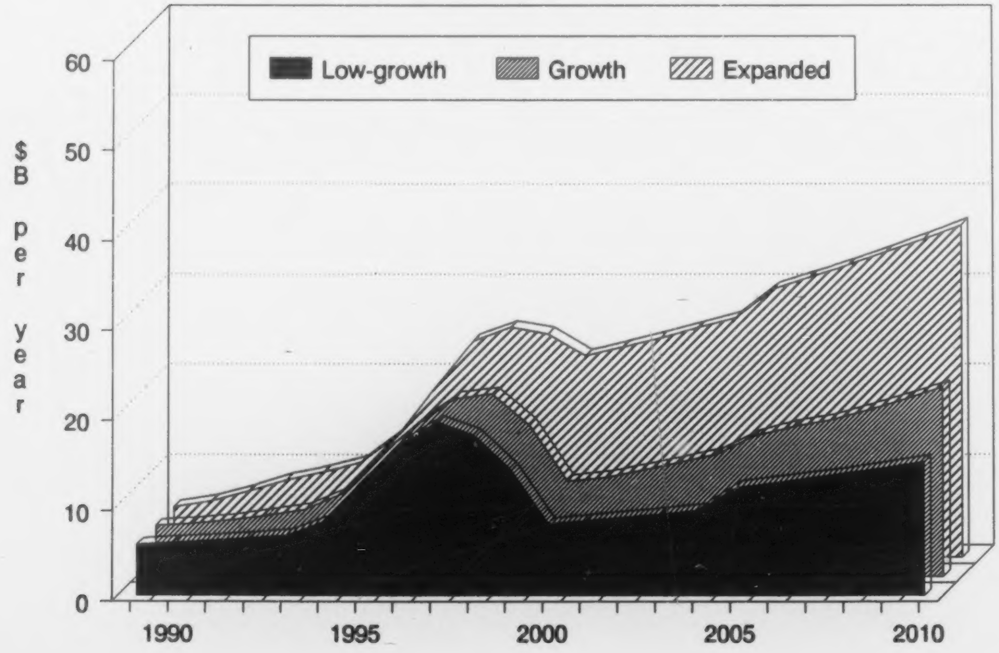


Figure B-7. – Funding Profiles for Advanced Option with Shuttle II



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OTA-ISC-383 JULY 1988

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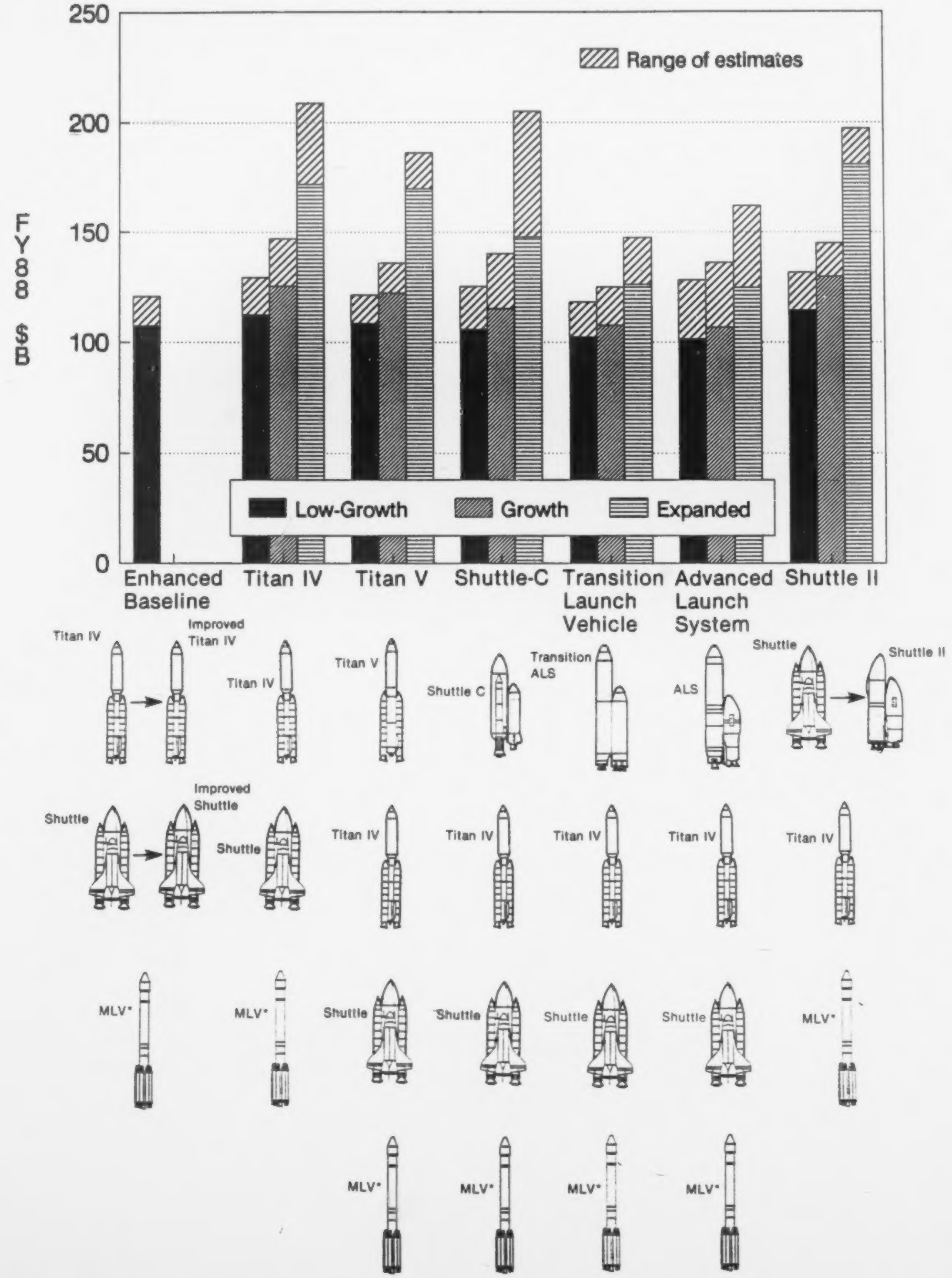
Figure 1-3.—Ranges of Estimates of Life-Cycle Costs
(1988 dollars, discounted at 5 percent)



*Medium Launch Vehicle

SOURCE: Office of Technology Assessment, 1988.